Measurement of Charge Dependent Directed Flow at RHIC

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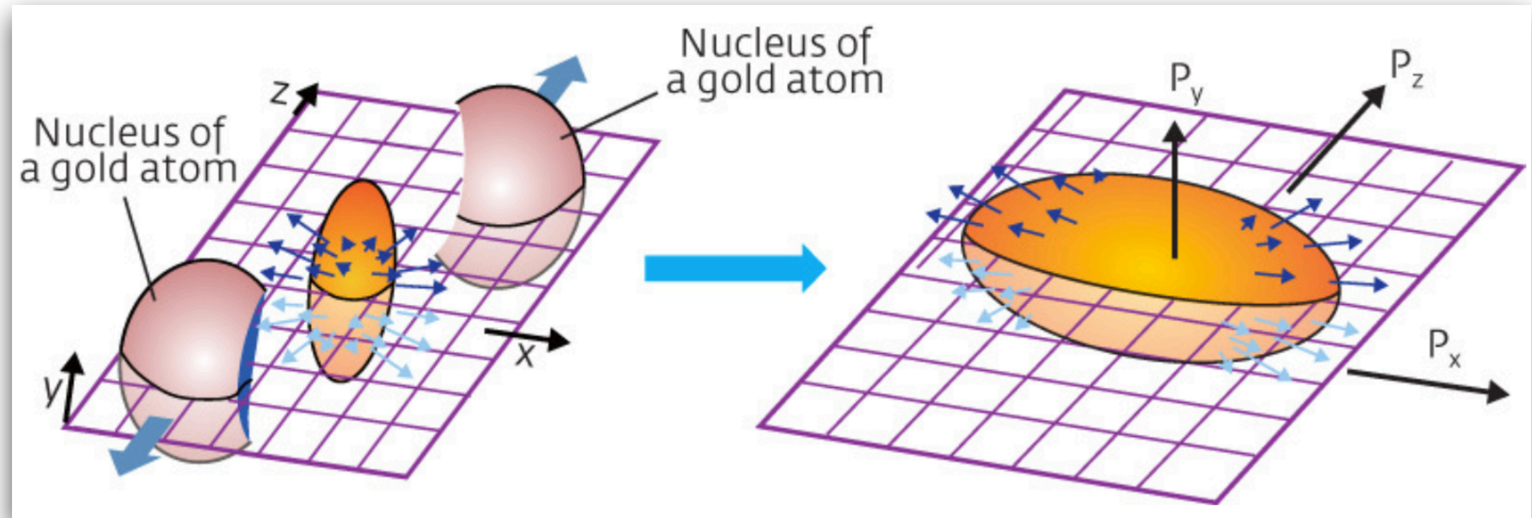
Outline

- Motivation (directed flow)
- Electromagnetic field effects in HIC
- STAR detector and event plane reconstruction
- Results of charge dependent directed flow (Δv_1)
    - Quark coalescence hypothesis
    - Δv_1 in asymmetric collisions (Cu+Au)
    - Δv_1 for charm hadrons
    - Δv_1 for Light hadrons
- Summary and outlook

Collective flow



Co-ordinate space anisotropy → **Momentum space anisotropy**

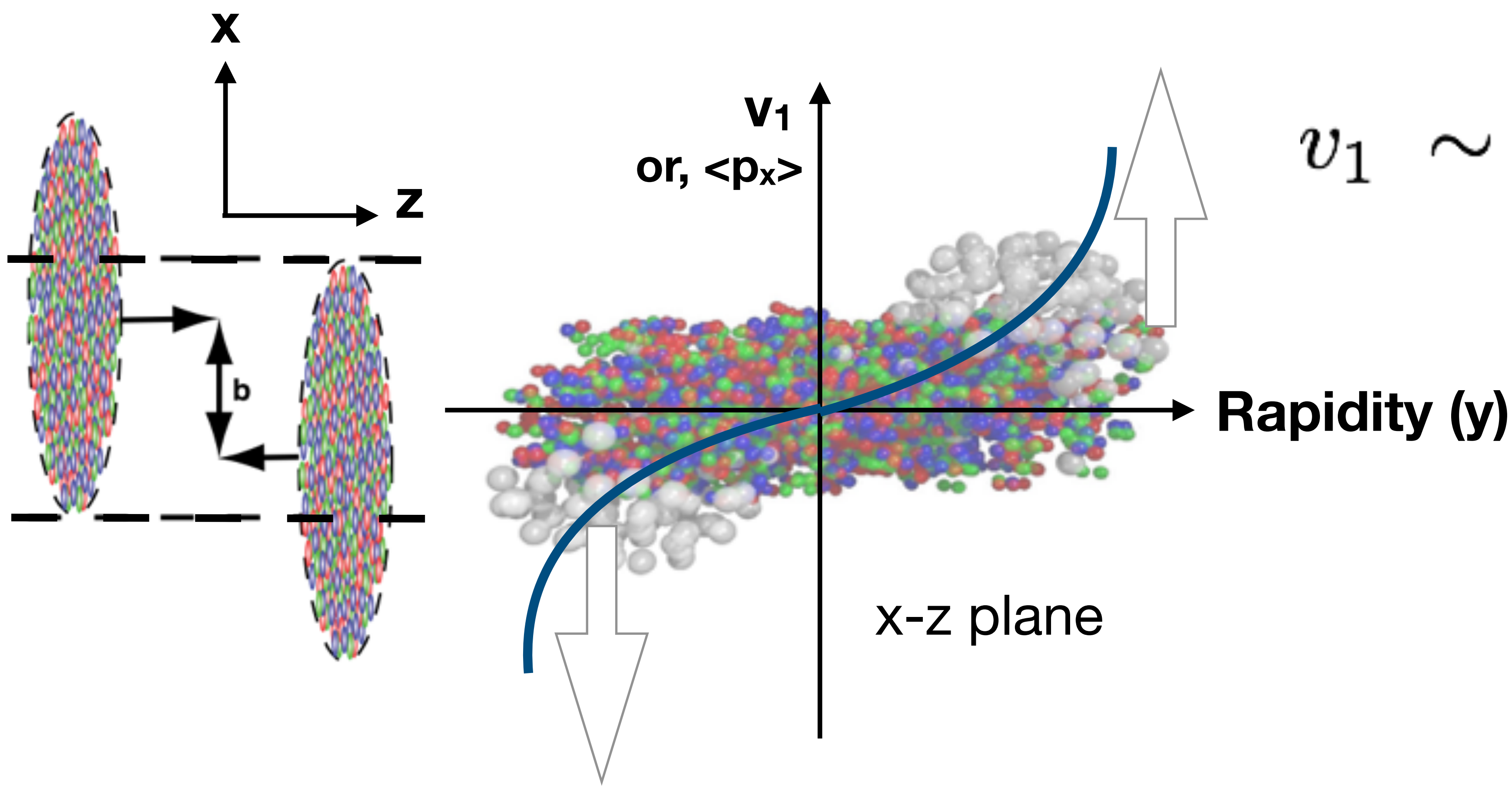
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum 2v_n \cos n(\phi - \Psi_n^{EP})\right)$$

<u>Observables</u>

- v_1 : Directed flow
- v_2 : Elliptic flow
- v_3 : Triangular flow

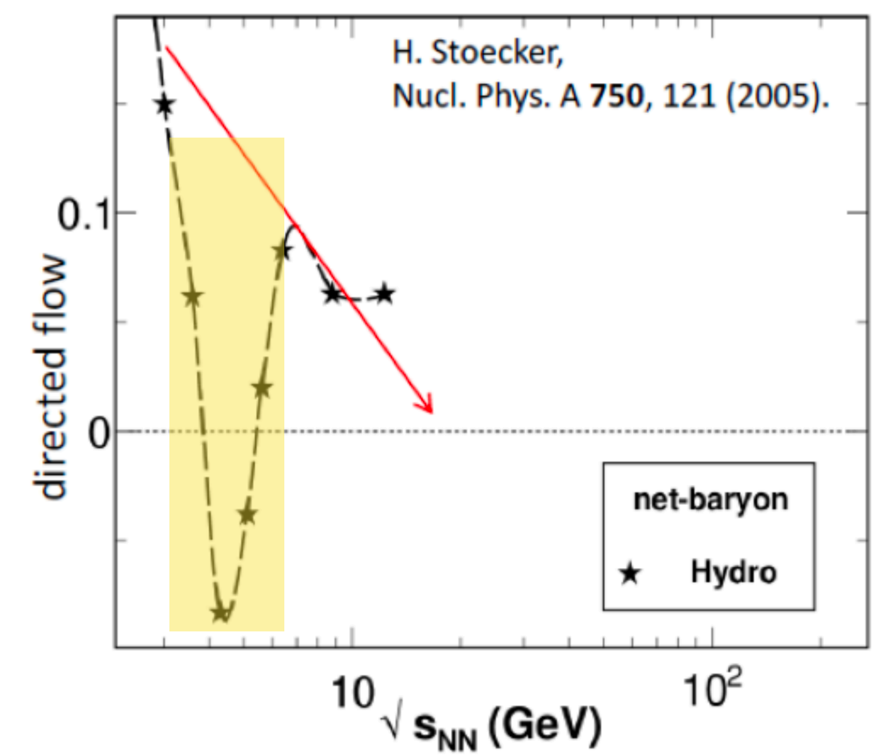
Flow coefficients are sensitive to:
initial/final state properties of the medium, EoS and degrees of freedom

Directed flow in heavy ion collisions



$$v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$$

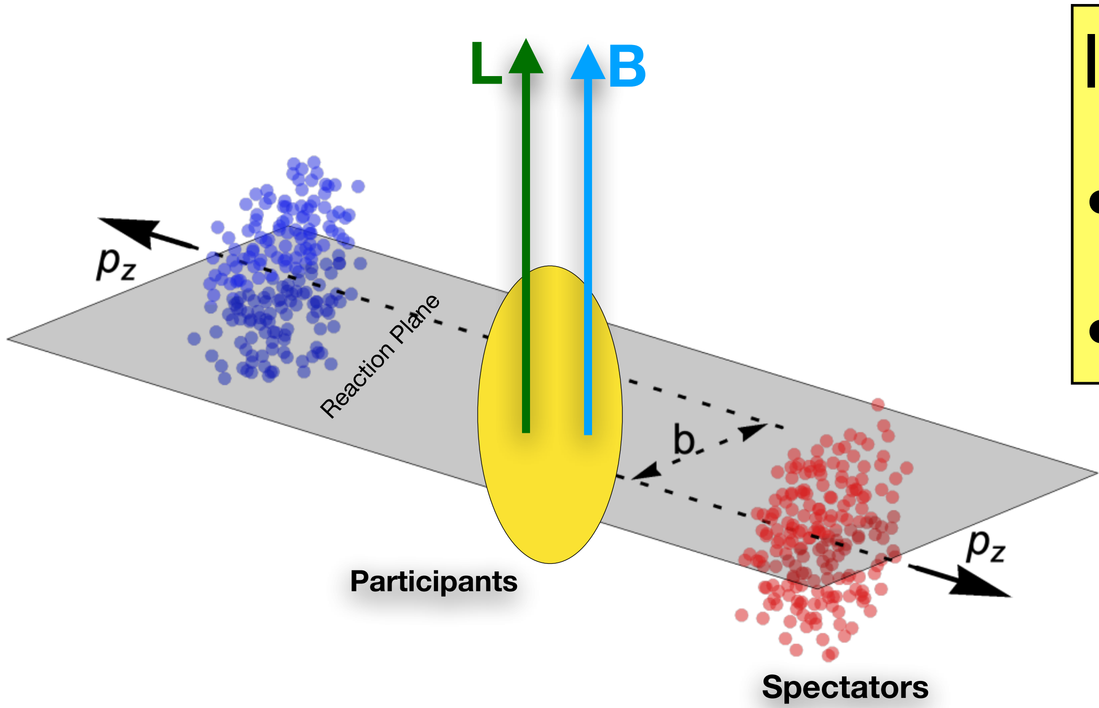
Hydro: Net-baryon v_1

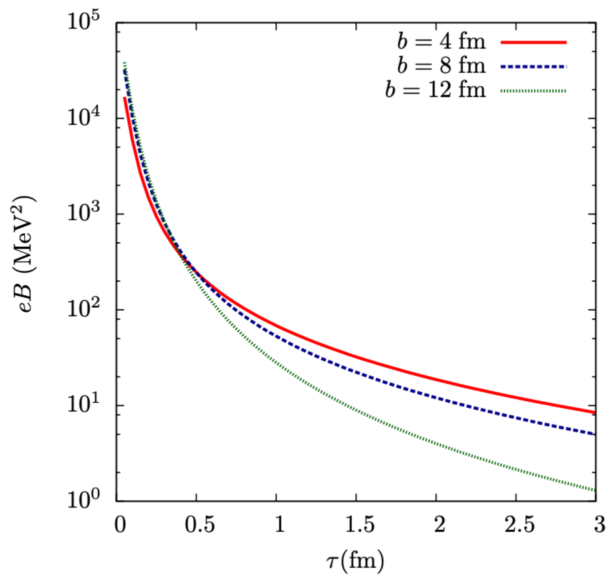


- Directed flow is the sideward collective motion of the produced particles within the reaction plane (x-z plane)
- Directed flow developed early in the collisions around time scale $2R/\gamma \sim 0.1$ fm/c
- Probe of early stage of collisions
- Sensitive to the pressure
- Sensitive to the EoS

- EoS **without** 1st order PT
  Monotonic energy dependence
- EoS **with** 1st order PT
  Non-Monotonic energy dependence, dip in dv_1/dy

QCD matter under extreme conditions





In non-central heavy-ion collisions

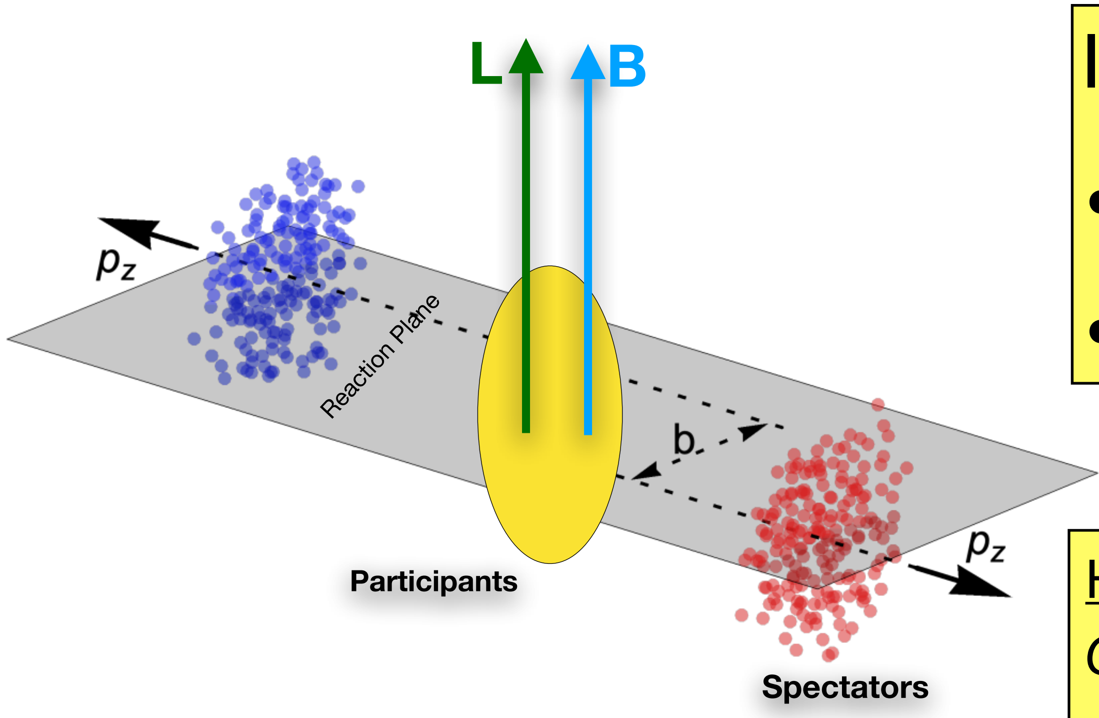
- **Initial rapid rotation** (ω ~ 10^{21} s^{-1})
- **Initial strong magnetic field** (B~ 10^{18} Gauss)

Earth's geomagnetic field ~ 0.5 G

Neutron star ~ 10^{14} G

- Ultra strong magnetic field can give rise wide range of exciting phenomena with applications in cosmology, neutron star and HIC

QCD matter under extreme conditions



In non-central heavy-ion collisions

- **Initial rapid rotation** (ω ~ 10^{21} s^{-1})
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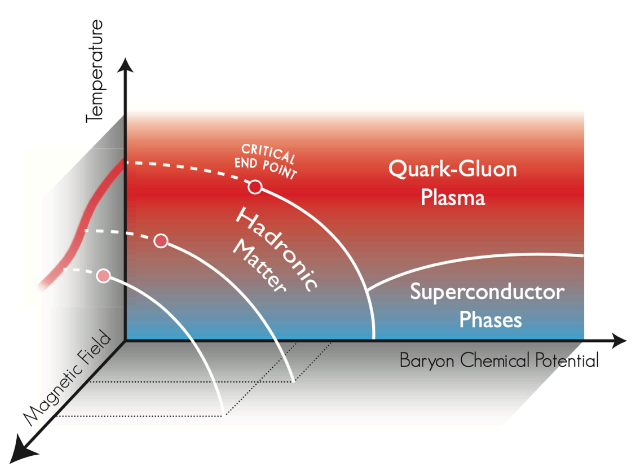
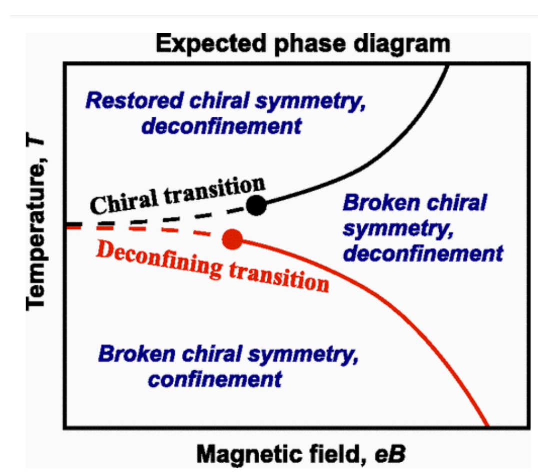
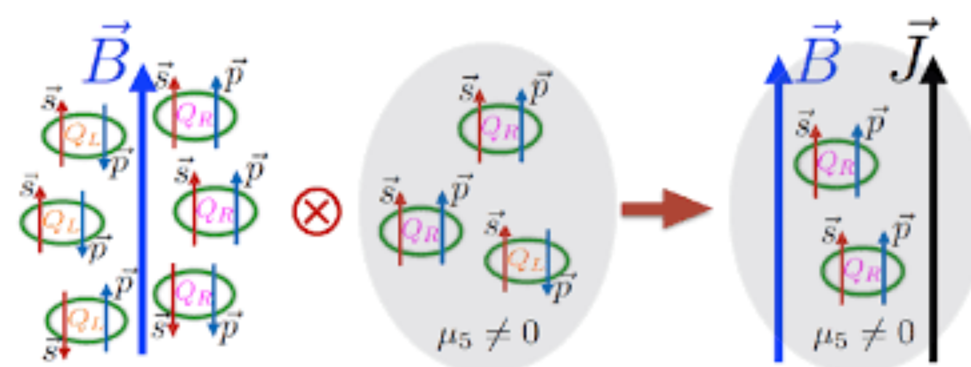
Heavy-ion collisions:
Controlled experiment to study QCD medium under rapid rotation and electro-magnetic field

→ *New frontier* research to understand The properties of QCD medium



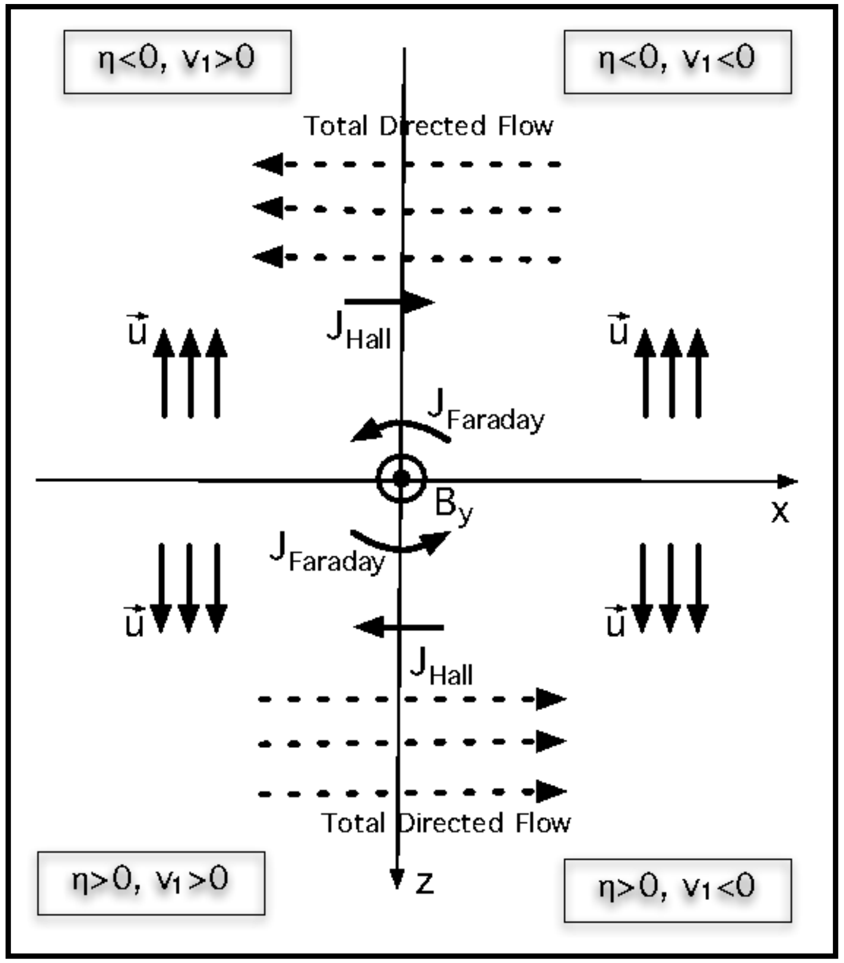


Impact on QCD phase transition, chiral symmetry restoration



Impact on QCD vacuum and its topology (Chiral Magnetic Effect)

Electromagnetic effects in HIC



Gursoy et al, PRC 89, 054905 (2014)

- The moving spectators can produce enormously large **B** field ($eB \sim 10^{18}$ G)
- There could be three competitive effects

- <u>Hall effect:</u> $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$
  Lorentz force exerts a sideways push on charged particles
  In opposite directions for opposite particles
  (along -ve X-direction in +ve rapidity and vice-versa)

- <u>Faraday effect:</u> $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
  Time dependent **B** field generates a large **E** field
  Induced Faraday current will oppose the drift due to **B** field

- <u>Coulomb effect:</u>
  Coulomb field of the charged spectators

<u>Observable</u>

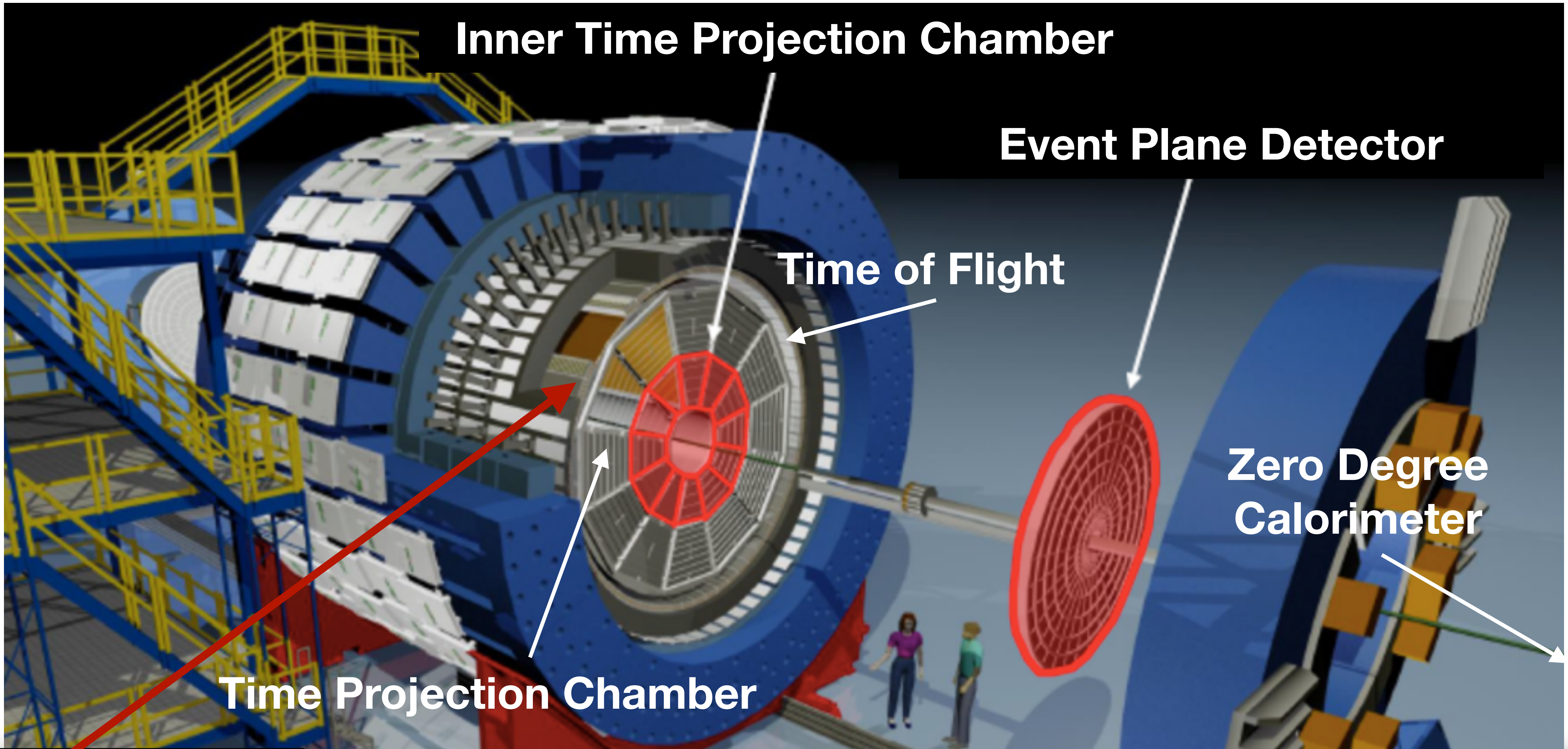
$$v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$$

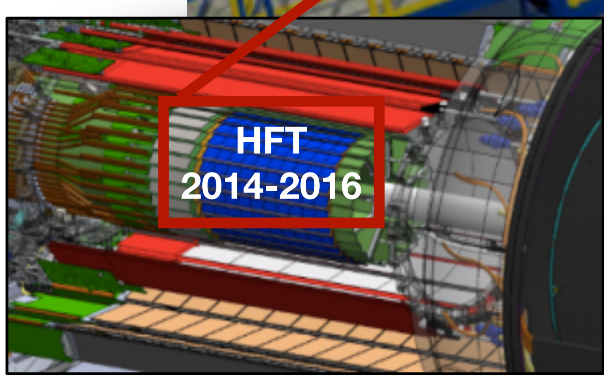
$$\Delta v_1 \sim v_1(h^+) - v_1(h^-)$$

(sensitive to EM effects)

- **Imprints of EM field effects**
- Hall: positive Δv_1
- Faraday: negative Δv_1
- Coulomb: negative Δv_1

STAR detector





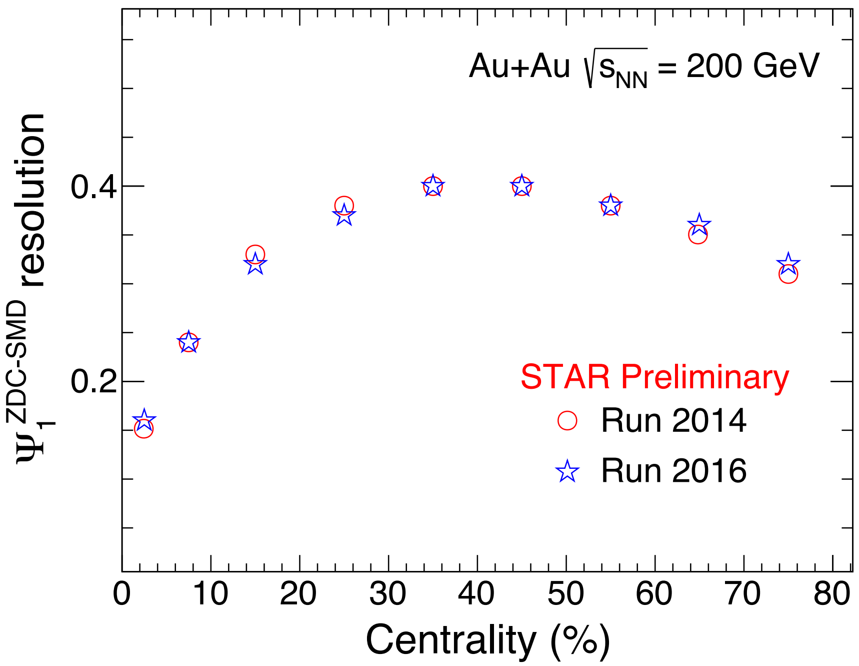
Heavy Flavor Tracker (2014-2016)

- Uniform acceptance, full azimuthal coverage, excellent PID capability
- <u>TPC</u>: tracking, centrality and event plane
- <u>EPD, ZDC, BBC</u>: event plane
- <u>TPC+TOF</u>: particle identification

Event plane reconstruction

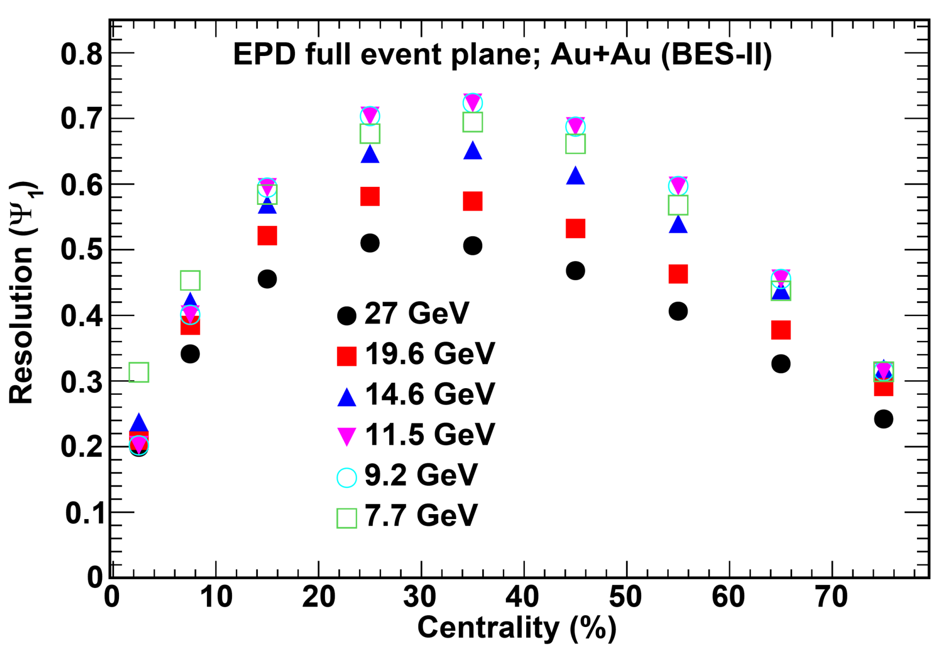
$$v_1 \sim \frac{\langle \cos(\phi - \Psi_{EP}) \rangle}{\text{EP} - \text{resolution}}$$

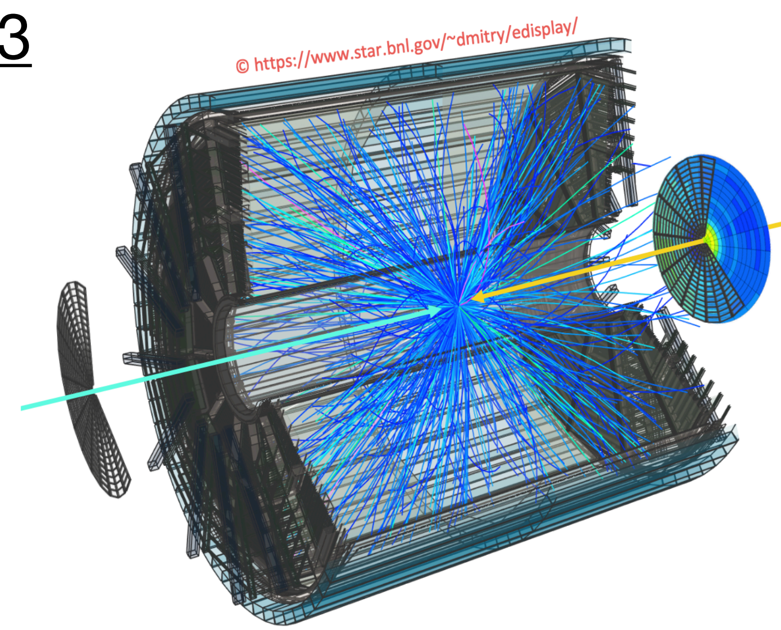
top-RHIC energy: ZDC-SMD |η|>6.4:

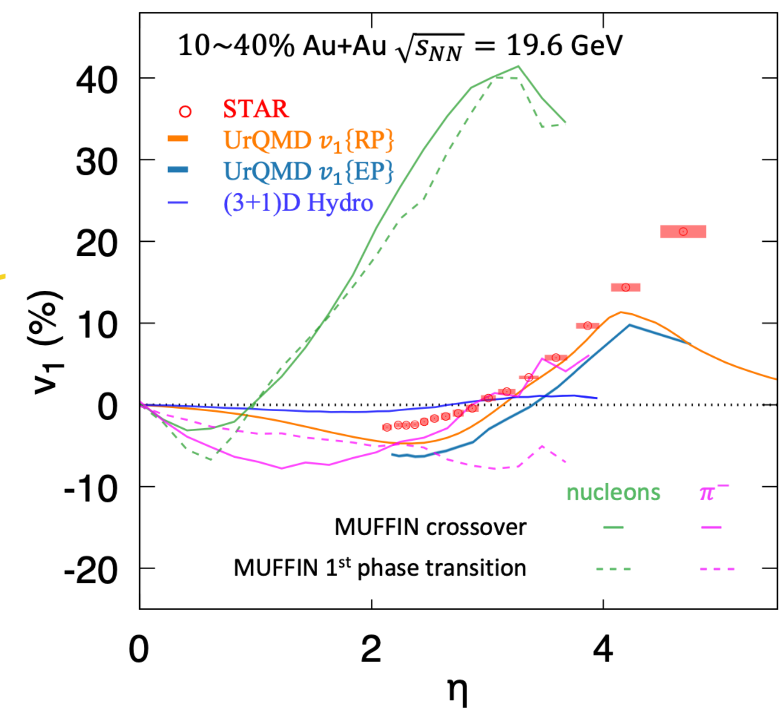


- v_1 signal is significant at forward rapidity
  Better ψ_1 resolution than mid-rapidity detectors
- Large η-gap significantly reduces non-flow contribution

BES-II (7.7 - 27 GeV): EPD 2.1<|η|<5.3







STAR: 2406.18213 (accepted in PRC)

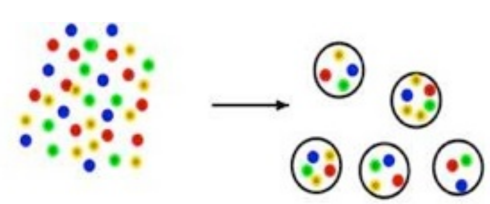
Quark coalescence using directed flow

Test the assumption that the de-confined quarks acquired v_n, then they form hadrons:

$$v_n^{\text{hadron}} = \sum v_n^{\text{constituent-quarks}}$$

The origin of scaling is interpreted as an evidence for dominance of quark degrees of freedom

Particle	Quark content
anti-Λ	uds
anti-p	uud
K-	us



qq vs. qqq

Quark coalescence hypothesis

Test the assumption that the de-confined quarks acquired v_n, then they form hadrons:

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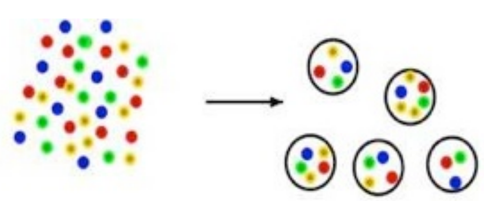
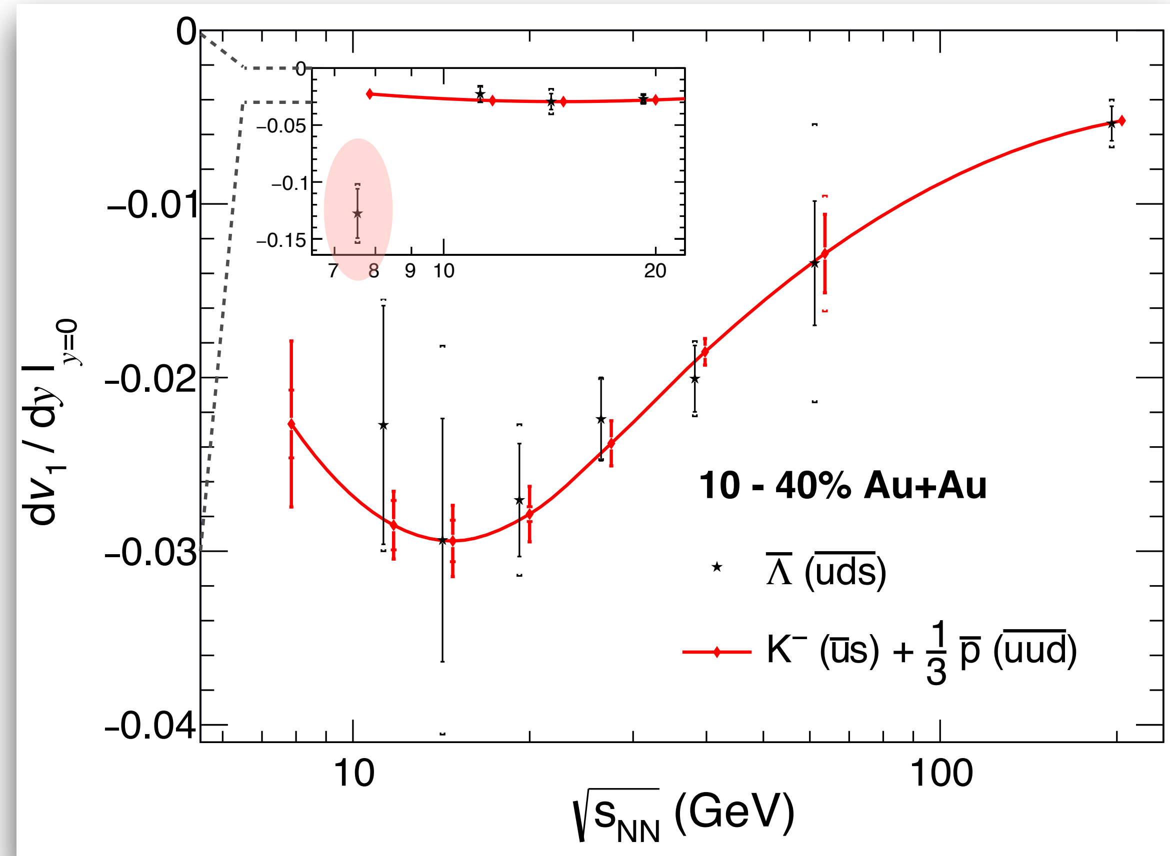


qq vs. qqq

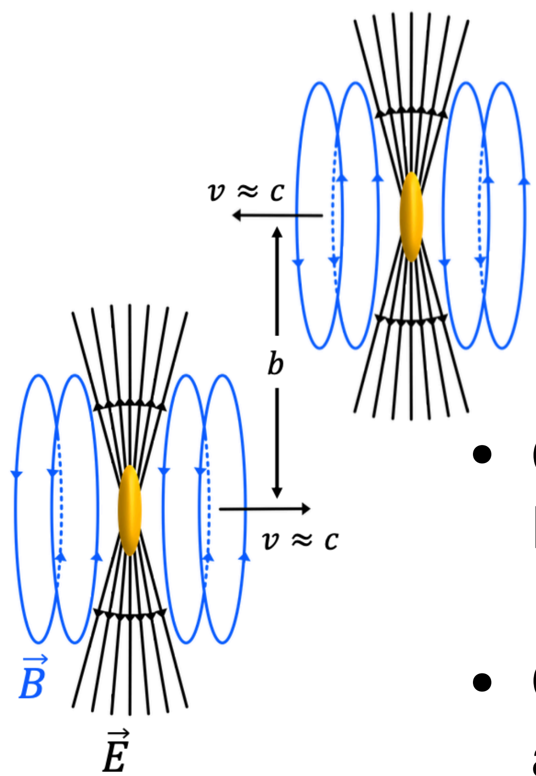


STAR: PRL 112, 162301 (2014)
PRL 120, 062301 (2018)

- Using anti-particles quark coalescence sum rule:
- Holds for $\sqrt{s_{NN}} \geq 11.5$ GeV
- Breaks at $\sqrt{s_{NN}} = 7.7$ GeV

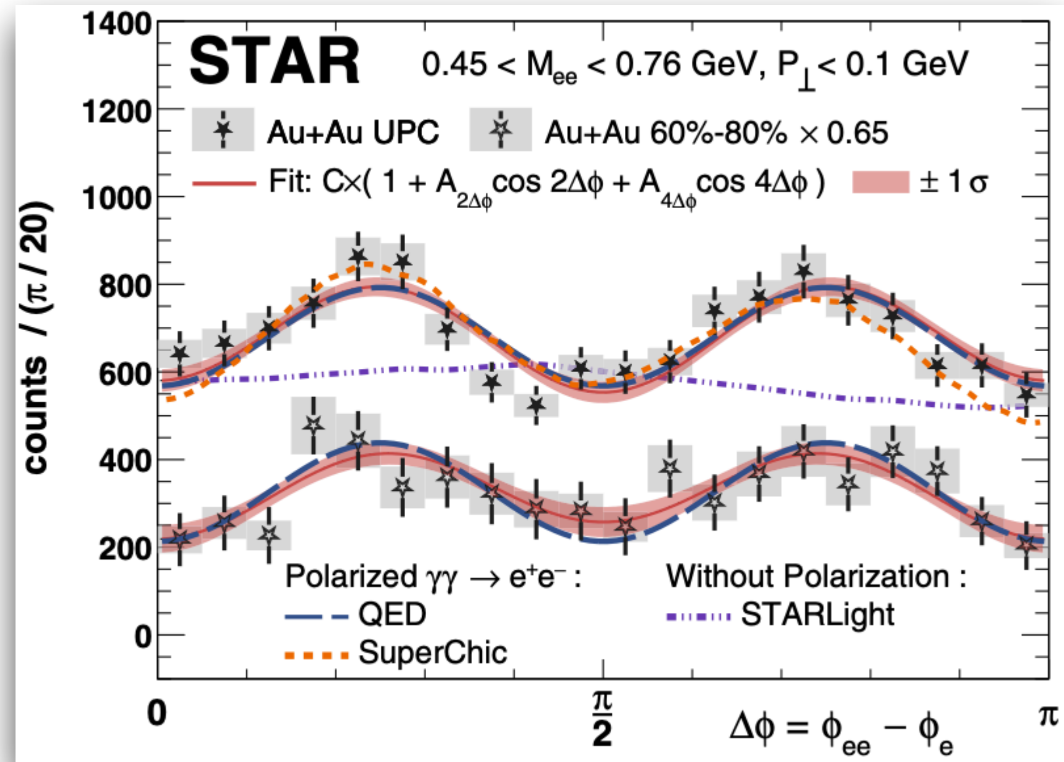
- Quark coalescence hypothesis holds over a broad range of energies

Electromagnetic field in UPC

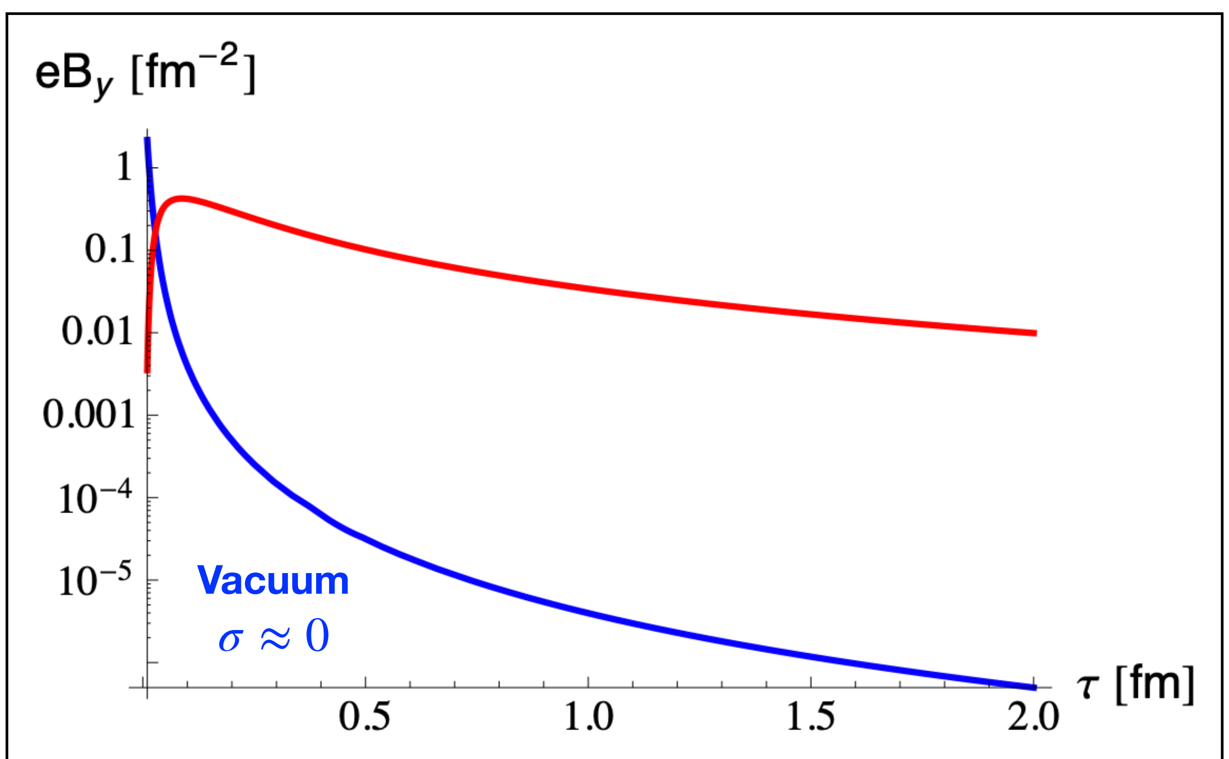


- Charged nuclei produce highly Lorentz contracted EM field
- Cross-sections for $\gamma\gamma \rightarrow e^+e^-$ are related to EM field strength and configuration

Ultra Peripheral Collisions (UPC)



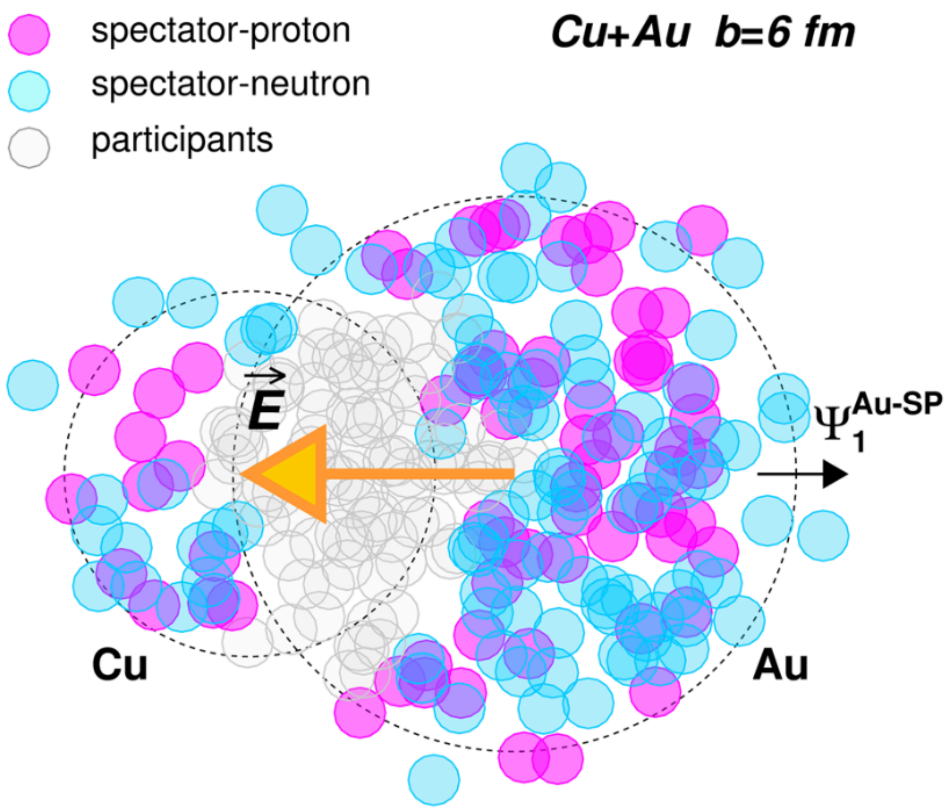
STAR, PRL 127, 052302 (2021)



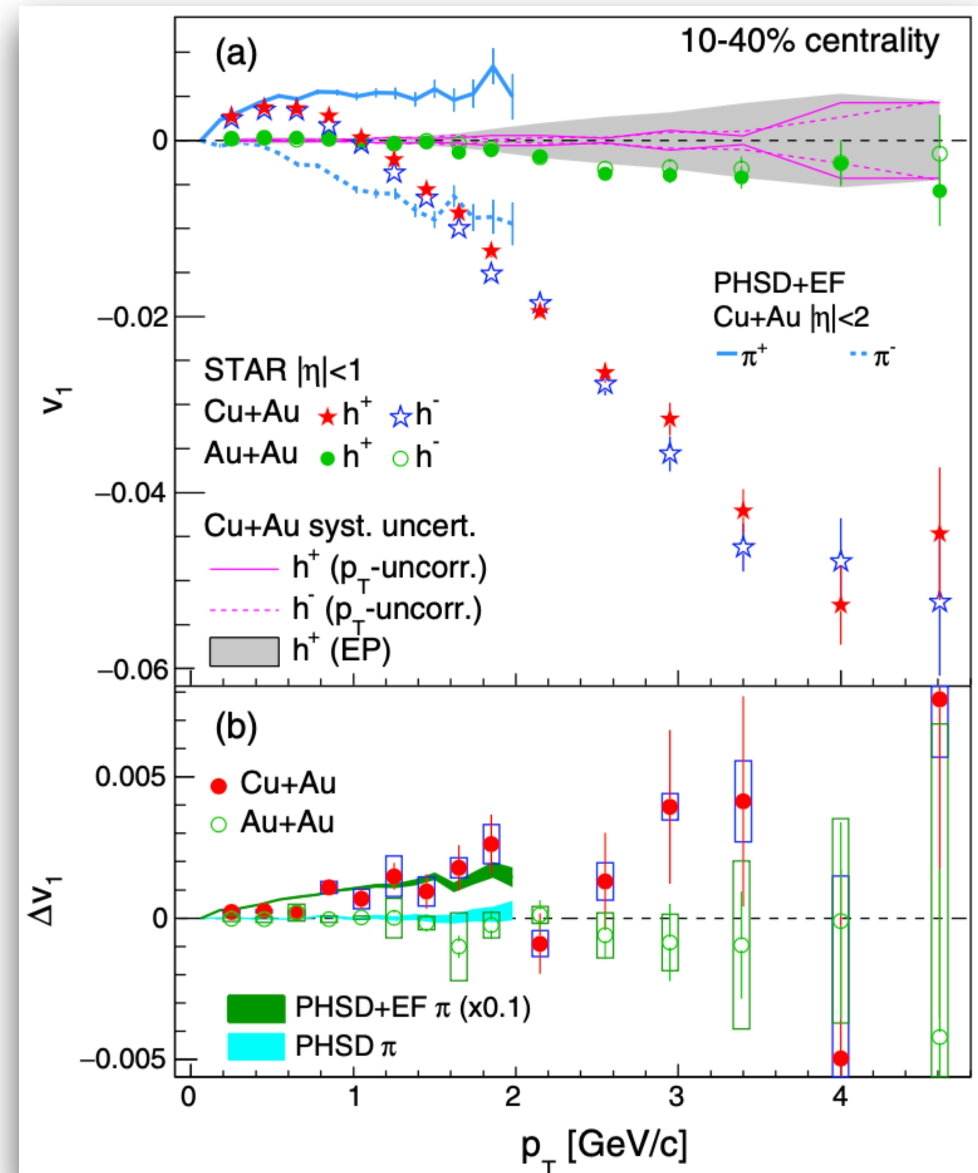
- Observed large $\cos(4\Delta\phi)$ modulation
- Features consistent with strong EM field

- No QGP medium
- B field in vacuum

Electric field in asymmetric collision system



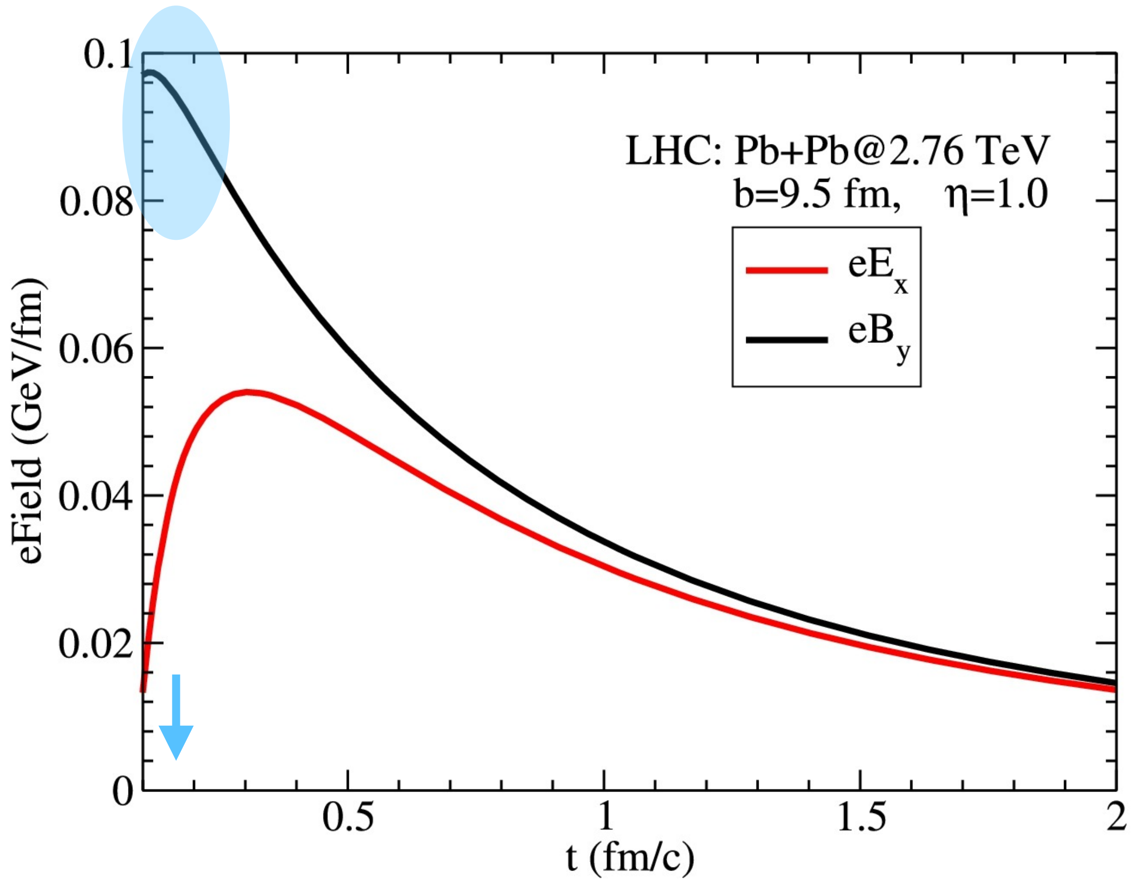
Inclusive charged particles

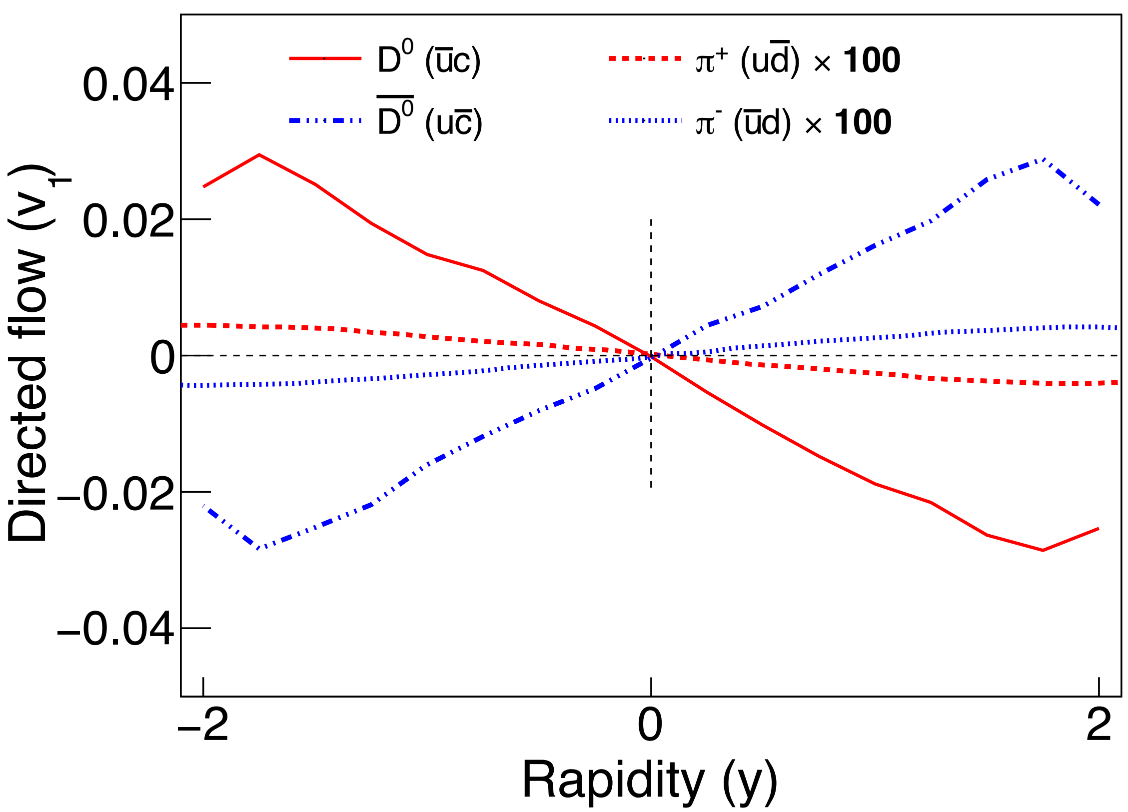


STAR, PRL 118, 012301 (2017)

- In asymmetric collision system → in-plane **E** field (Coulomb effect)
- Δv_1 in Cu+Au qualitatively agrees with expectation
- Can constrain electrical conductivity of the medium

Charm hadron directed flow splitting





Das et al, PLB 768, 260 (2017)

<u>Charm quark</u>

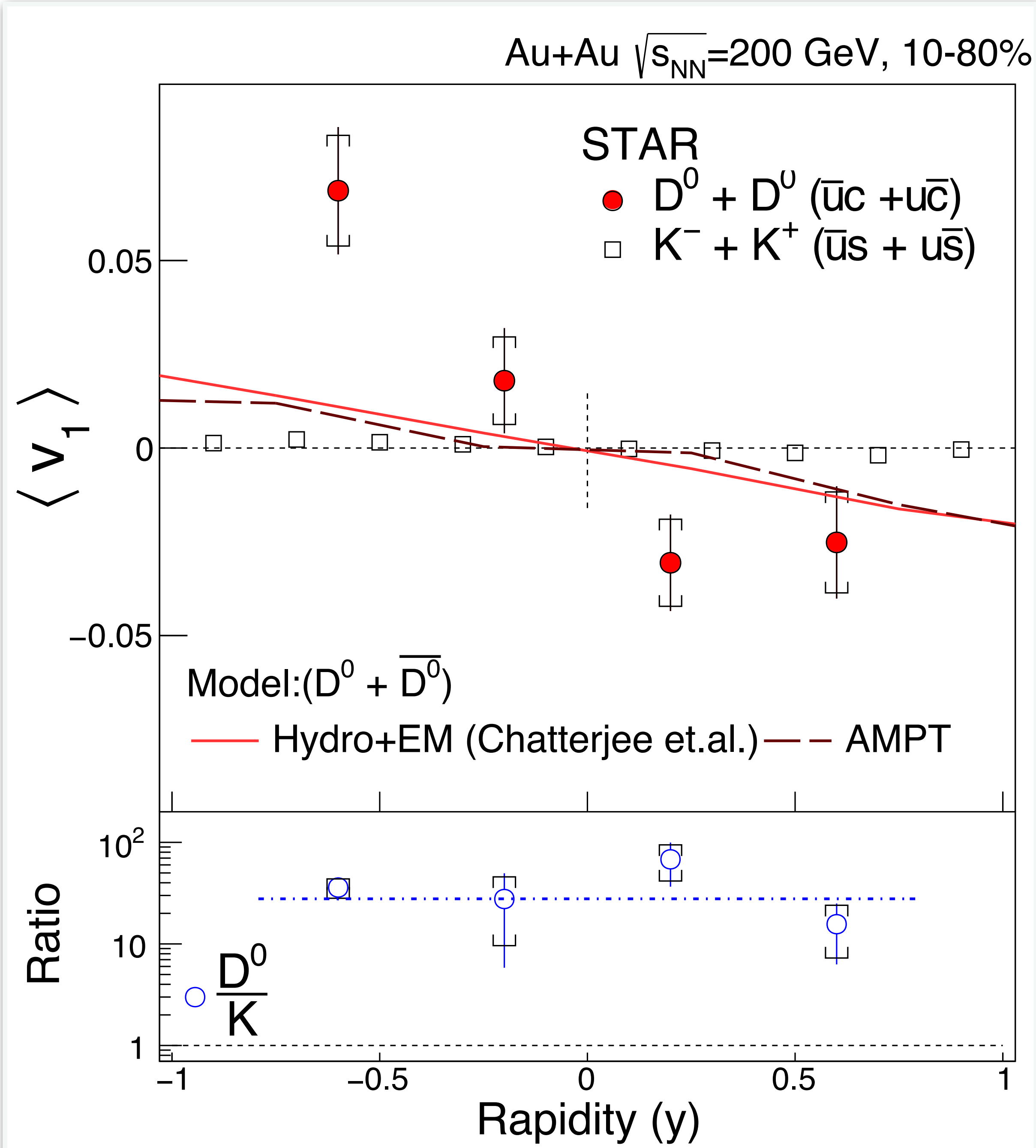
Formation time: τ_{CQ}~ 0.1 fm/c
Long relaxation time

Sensitive to early time B-field
Can retain its memory

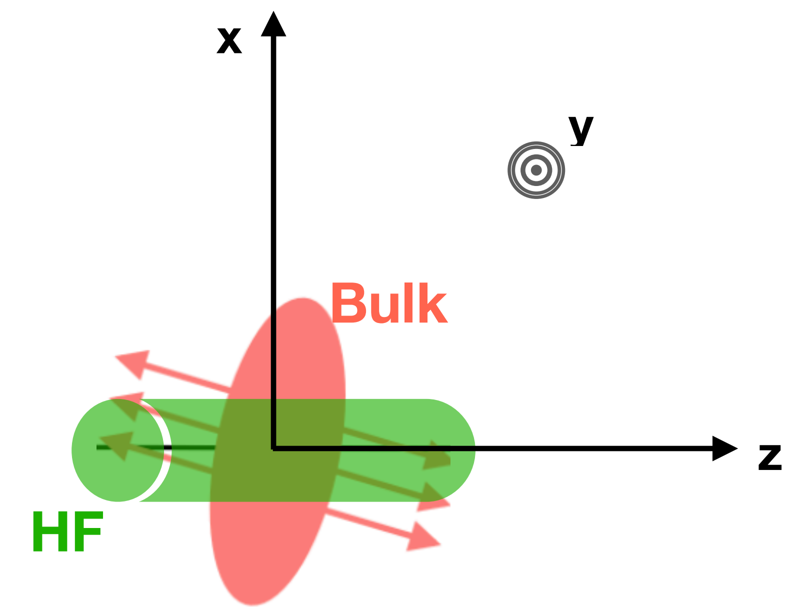
- B field in QGP

- Predicted splitting at a measurable range for charm hadrons
- Δv_1 (charm quark) >> Δv_1 (light quark)

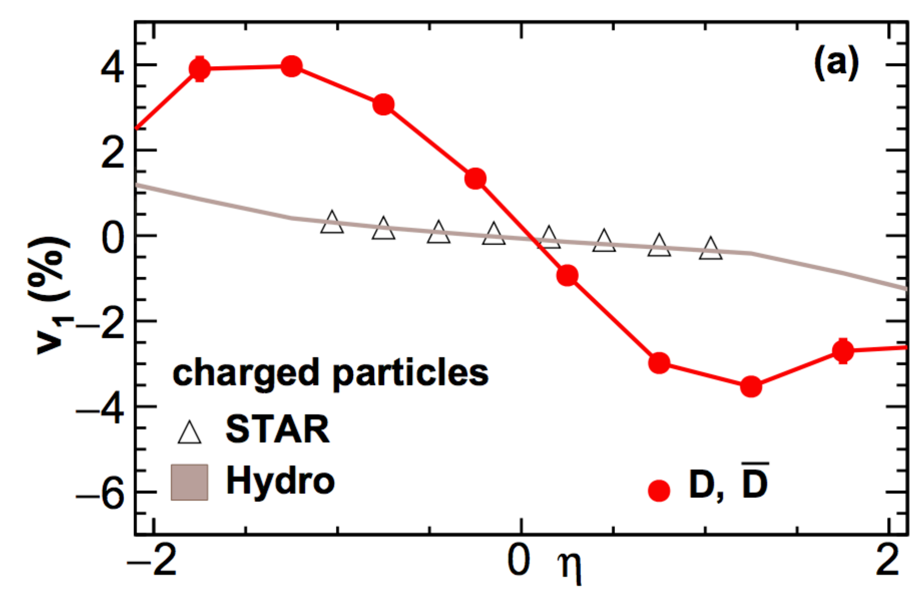
Observation of D^0 directed flow



STAR, PRL 123, 162301 (2019)



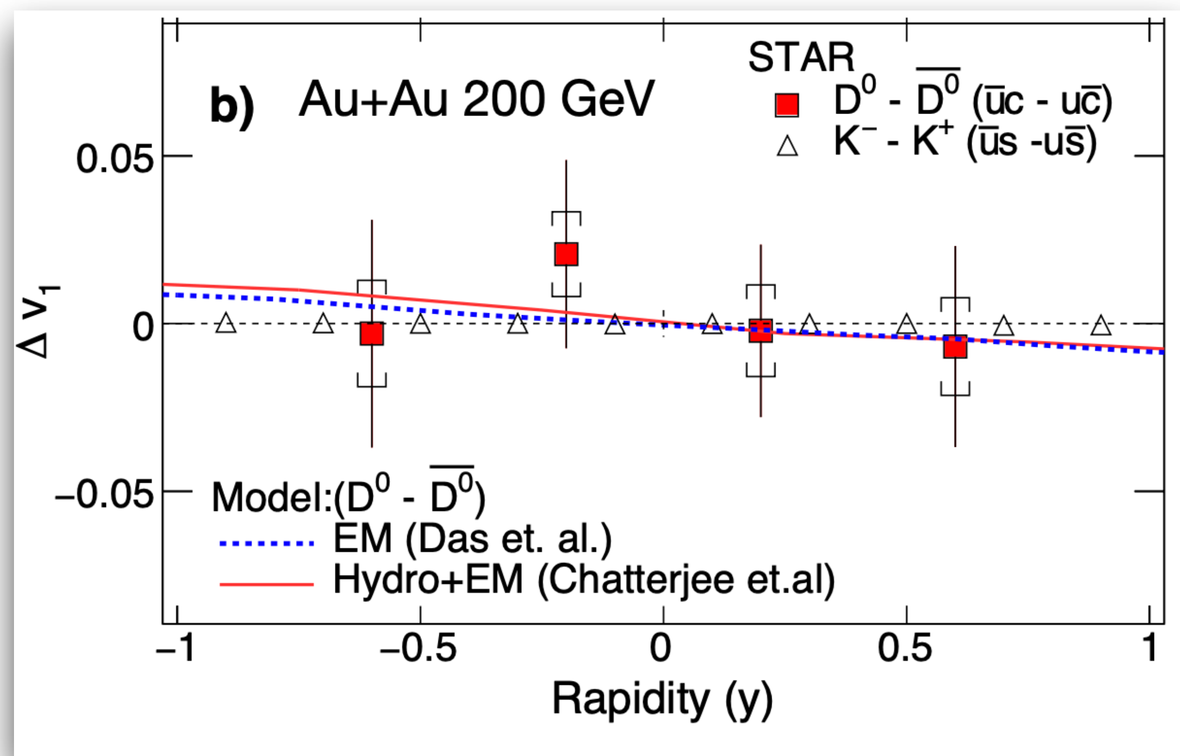
Drag force between the tilted bulk and the HFs



- First observation of non zero charm v_1
- v_1: $D^0 >> K$

Charge dependent D^0 directed flow (Δv_1)

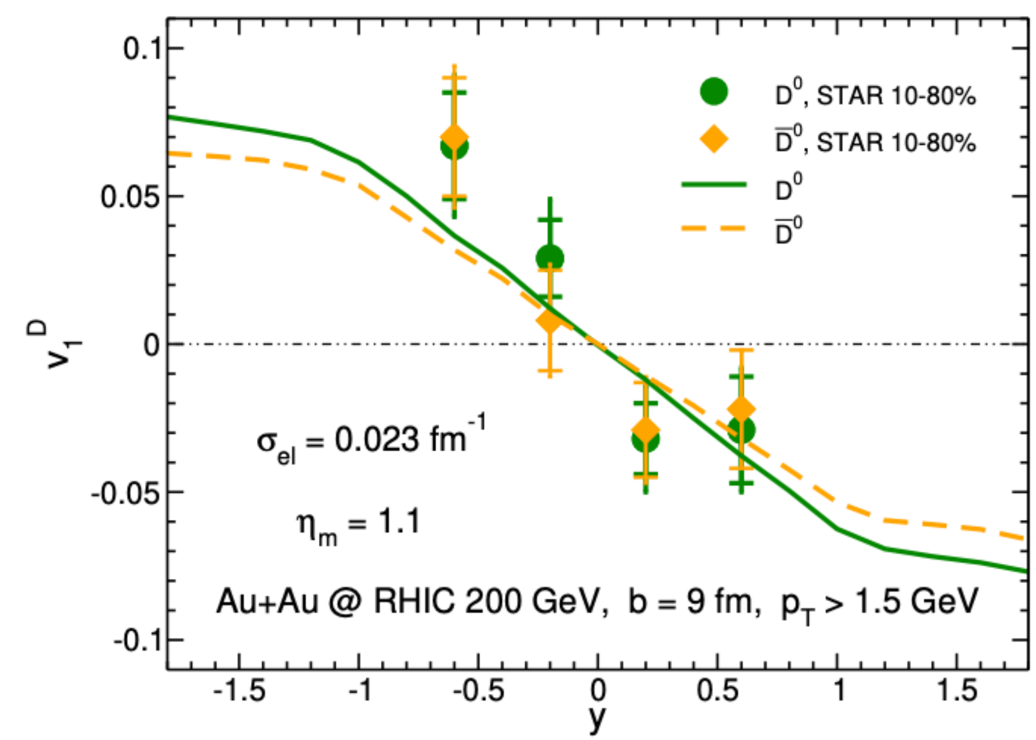
STAR



STAR, PRL 123, 162301 (2019)

Model: with electrical conductivity of QGP

$\sigma \sim 0.023\ \mathrm{fm}^{-1}$



Oliva et al, *JHEP* 05, 034 (2021)

- First attempt to probe EM field effects via charm v_1
- Δv_1 were inconclusive, not enough precision to constrain QGP conductivity

Charge dependent charm hadron directed flow

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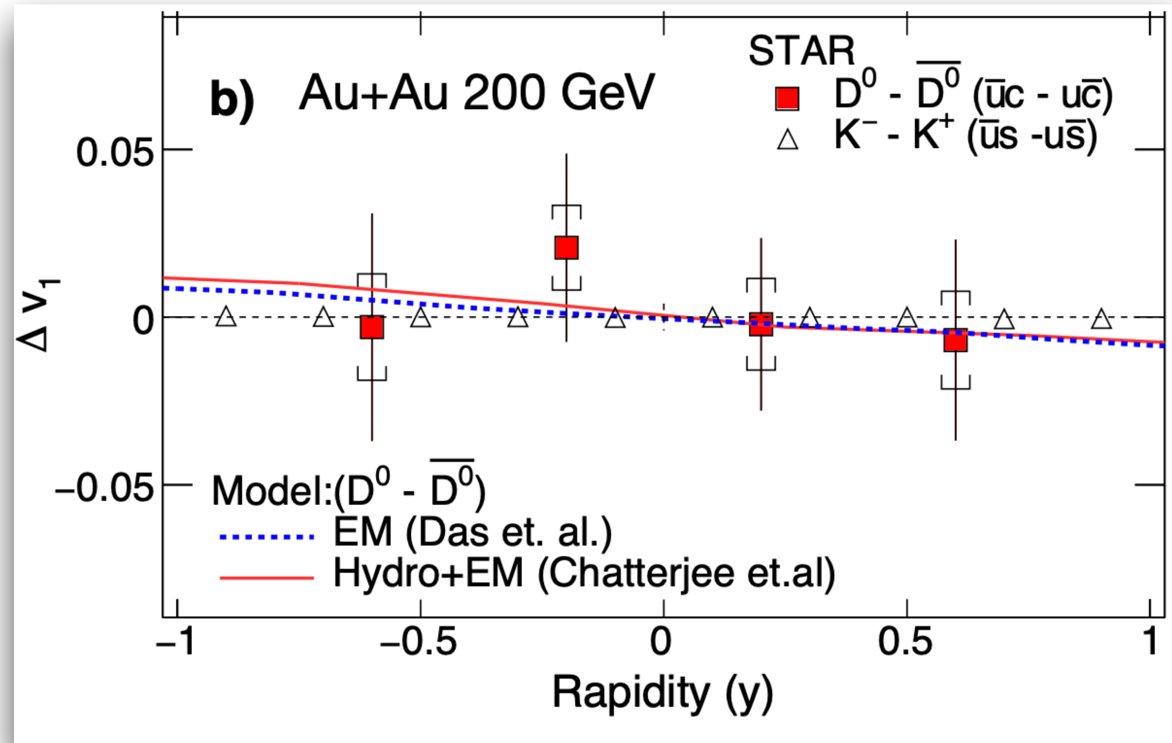
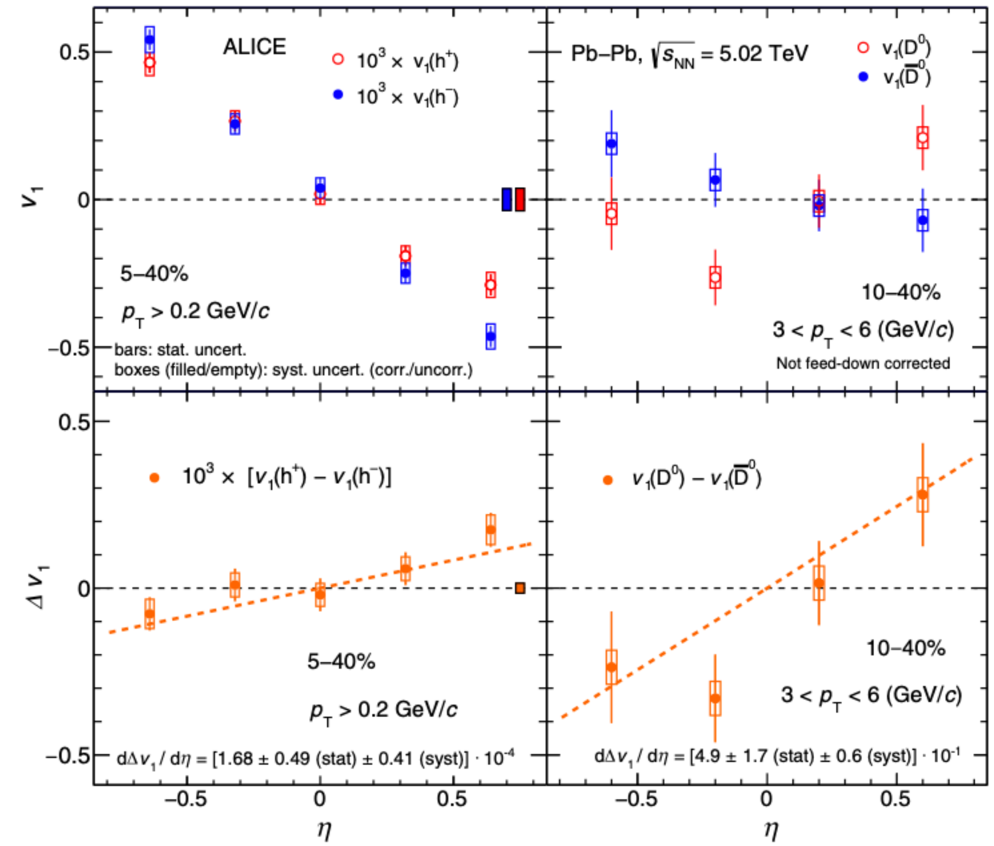


Not sufficient precision at STAR

ALICE

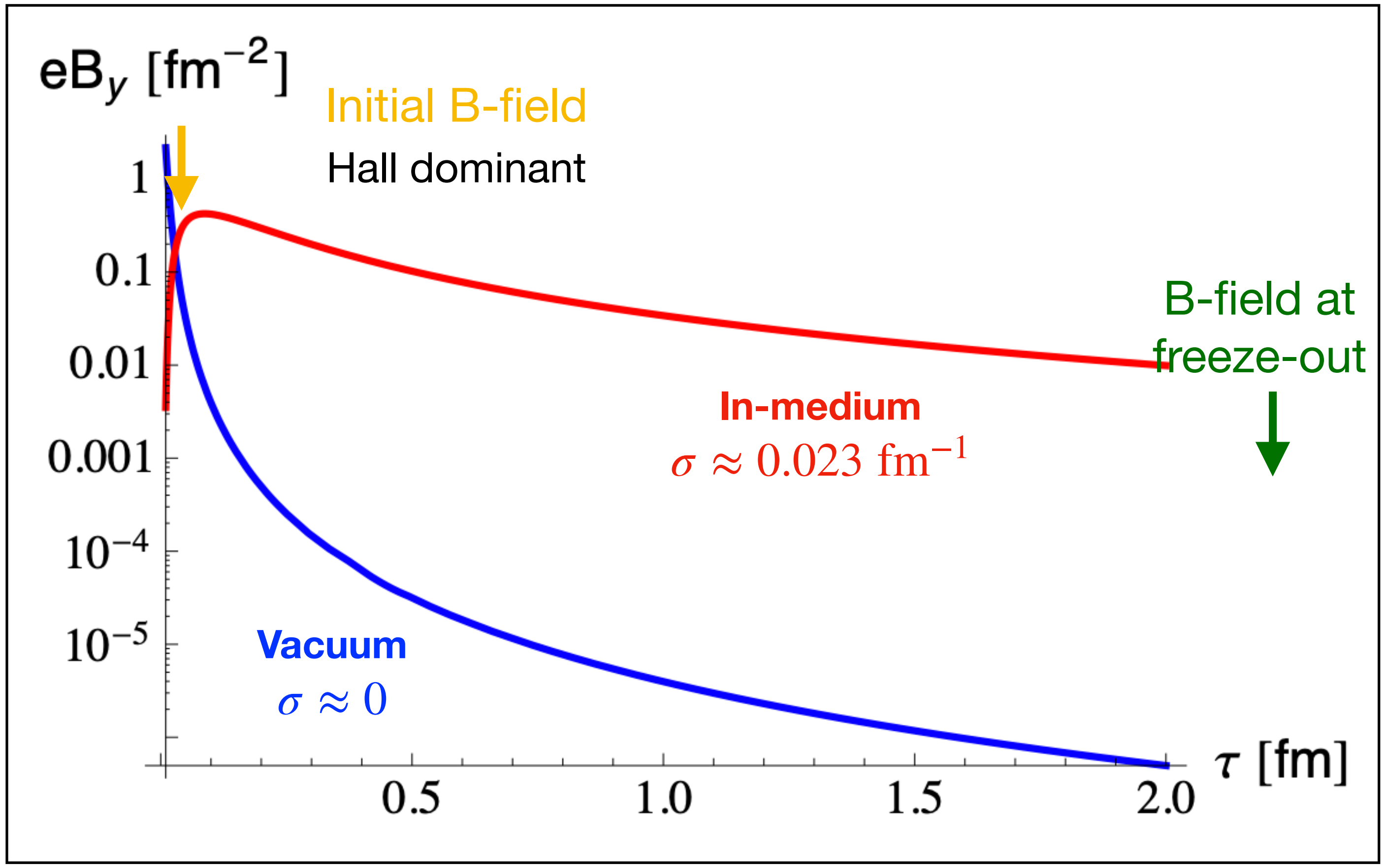


Not sufficient precision at ALICE
(Run-3 can provide good precision)

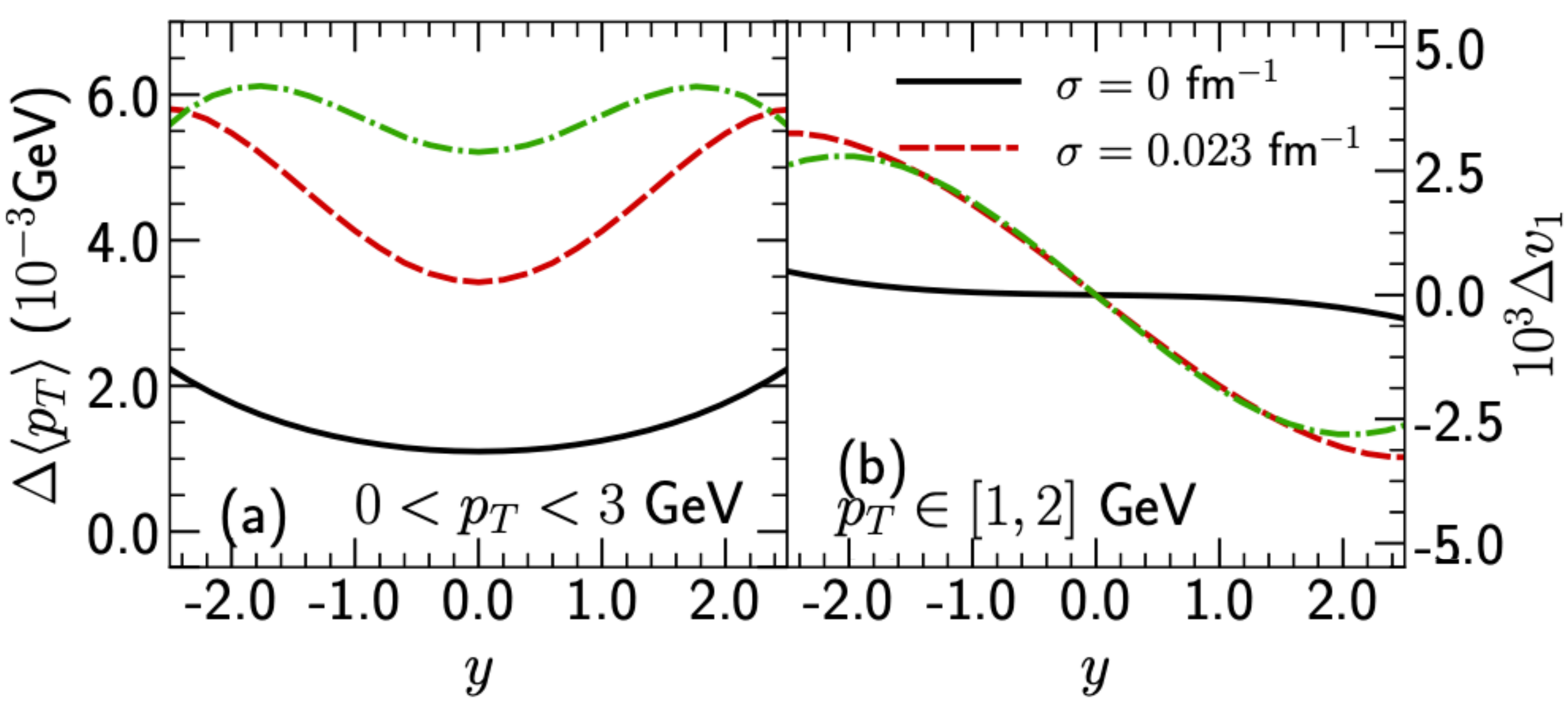
- First attempt to probe EM field effects via charm v_1
- Δv_1 were inconclusive for both RHIC and LHC

Charm hadrons are promising probe but challenging …

Charge dependent light hadron directed flow



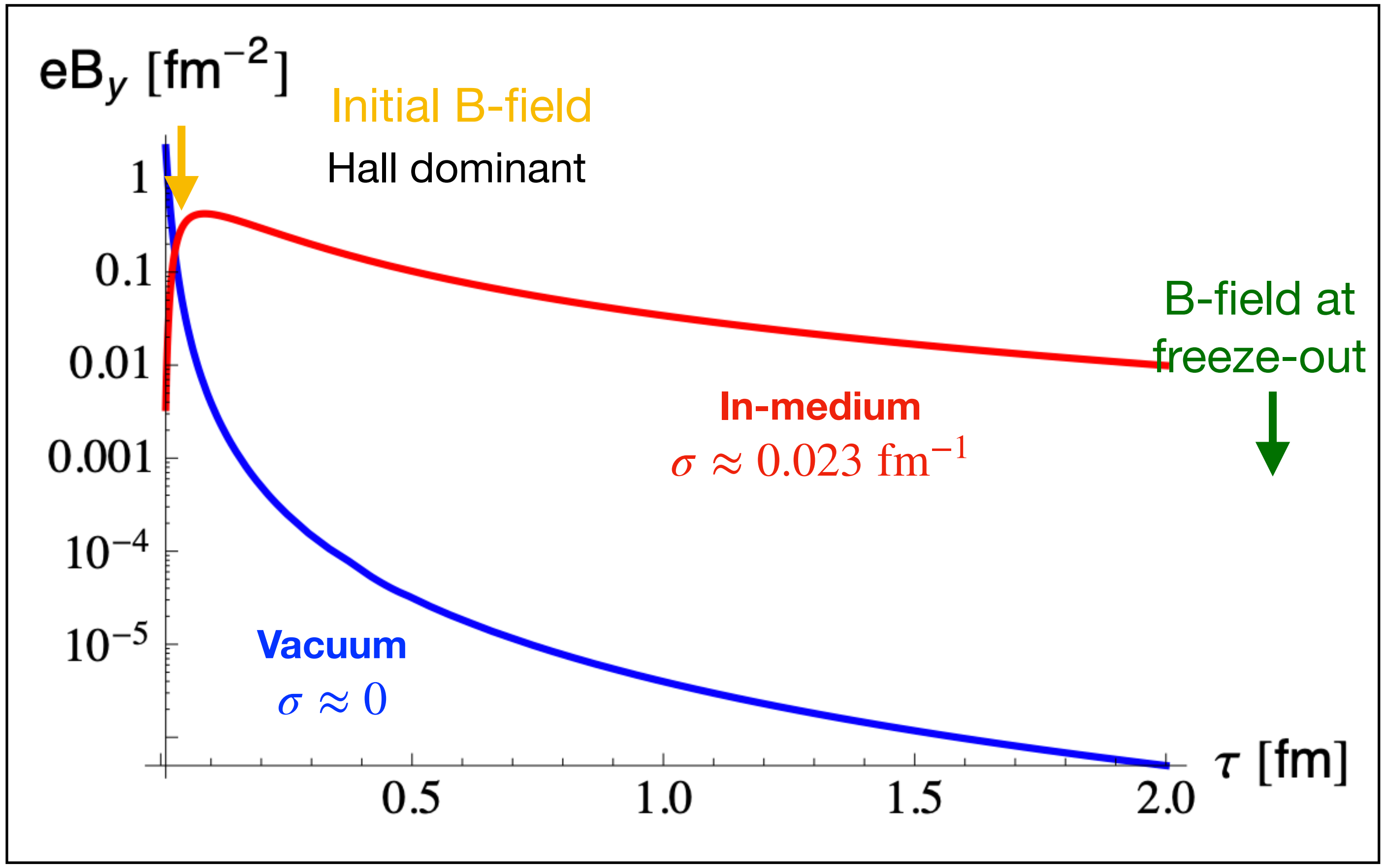
- **Imprints of EM field effects**
- Hall: positive Δv_1
- Faraday: negative Δv_1
- Coulomb: negative Δv_1



- Δv_1 sensitive to QGP conductivity

Gursoy et al, PRC 98, 055201 (2018)

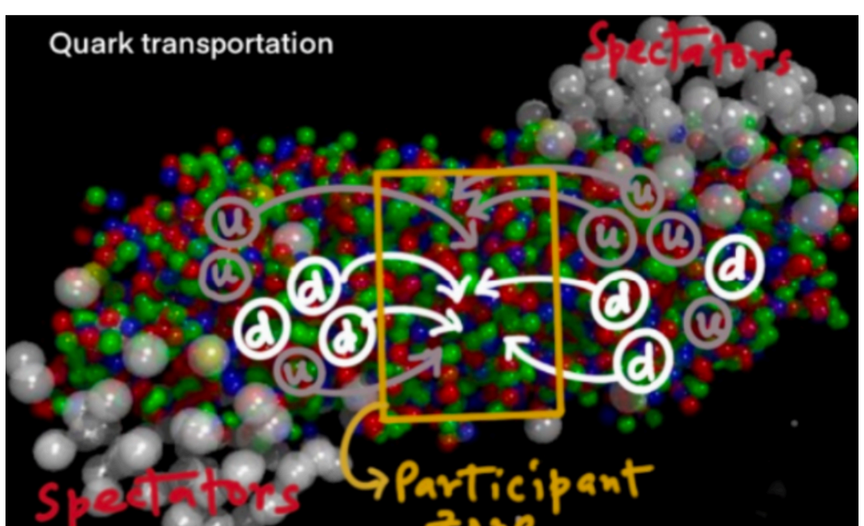
Charge dependent light hadron directed flow



- **Imprints of EM field effects**
- Hall: positive Δv_1
- Faraday: negative Δv_1
- Coulomb: negative Δv_1

- **Non-EM field effects**
- Transport: $\Delta v_1^{\dagger} \neq 0$
- ....

Transported quark effect: $\Delta v_1 \neq 0$



"*u*" and "*d*" quarks transported from incoming nuclei towards mid-rapidity

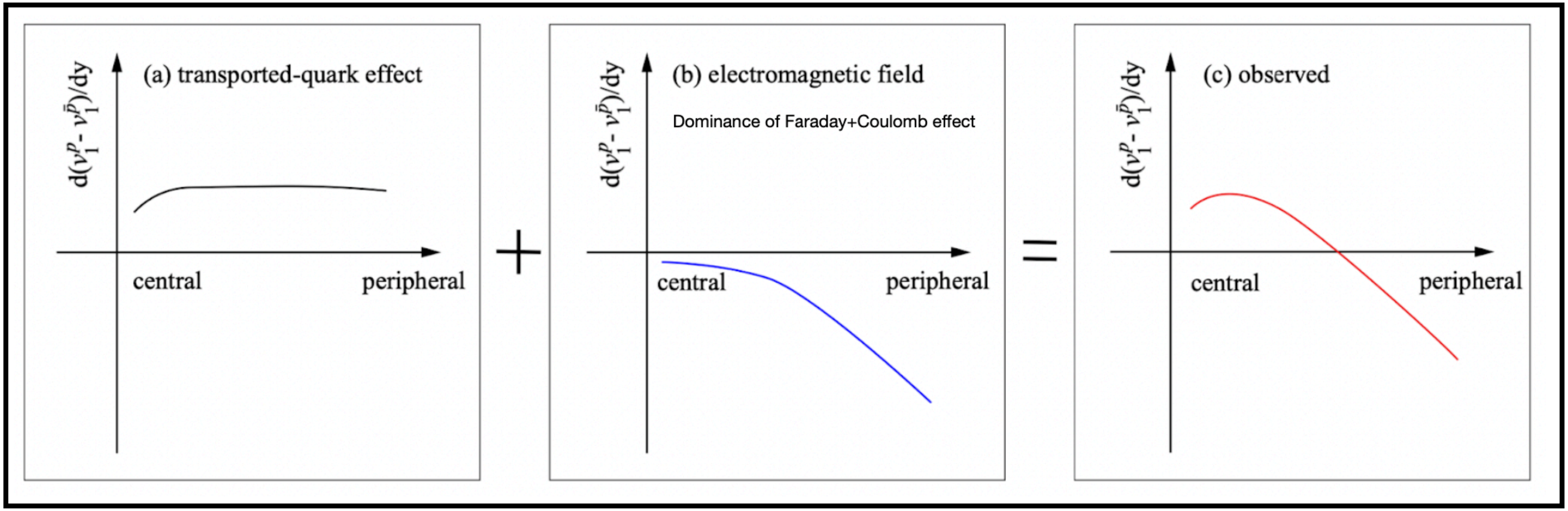
$p : uud$ $\quad \frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$
$\bar{p} : \bar{u}\bar{u}\bar{d}$

$K^+ : u\bar{s}$ $\quad \frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$
$K^- : \bar{u}s$

$\pi^+ : u\bar{d}$ $\quad \frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} < 0$
$\pi^- : \bar{u}d$
(#d>#u, Au neutron rich)

Charge dependent light hadron directed flow

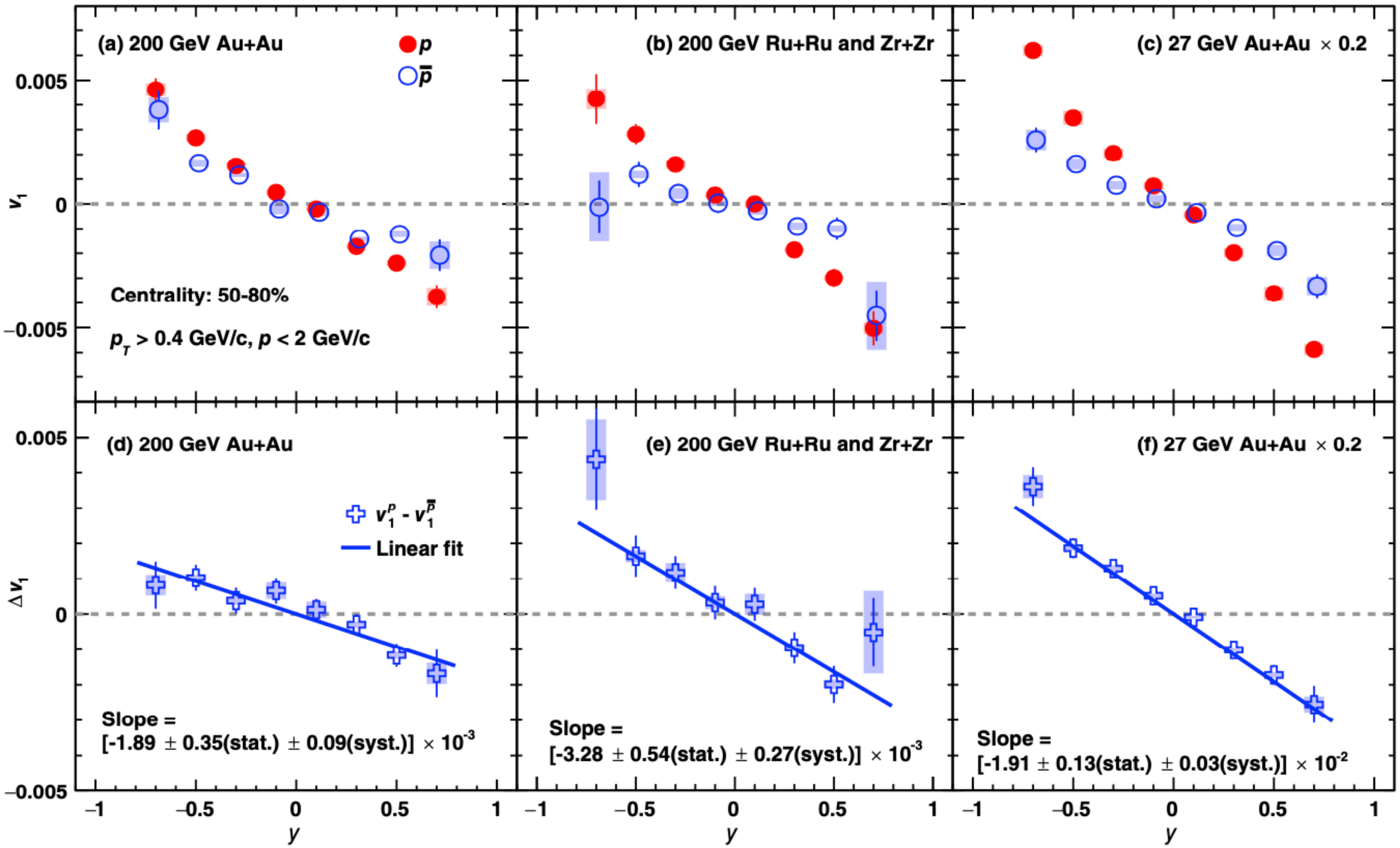
- Naive expectation for protons: EM field + transport



- For protons Δv_1 can change sign

  (if Faraday+Coulomb dominates over Hall effect)

Light hadron directed flow v_1

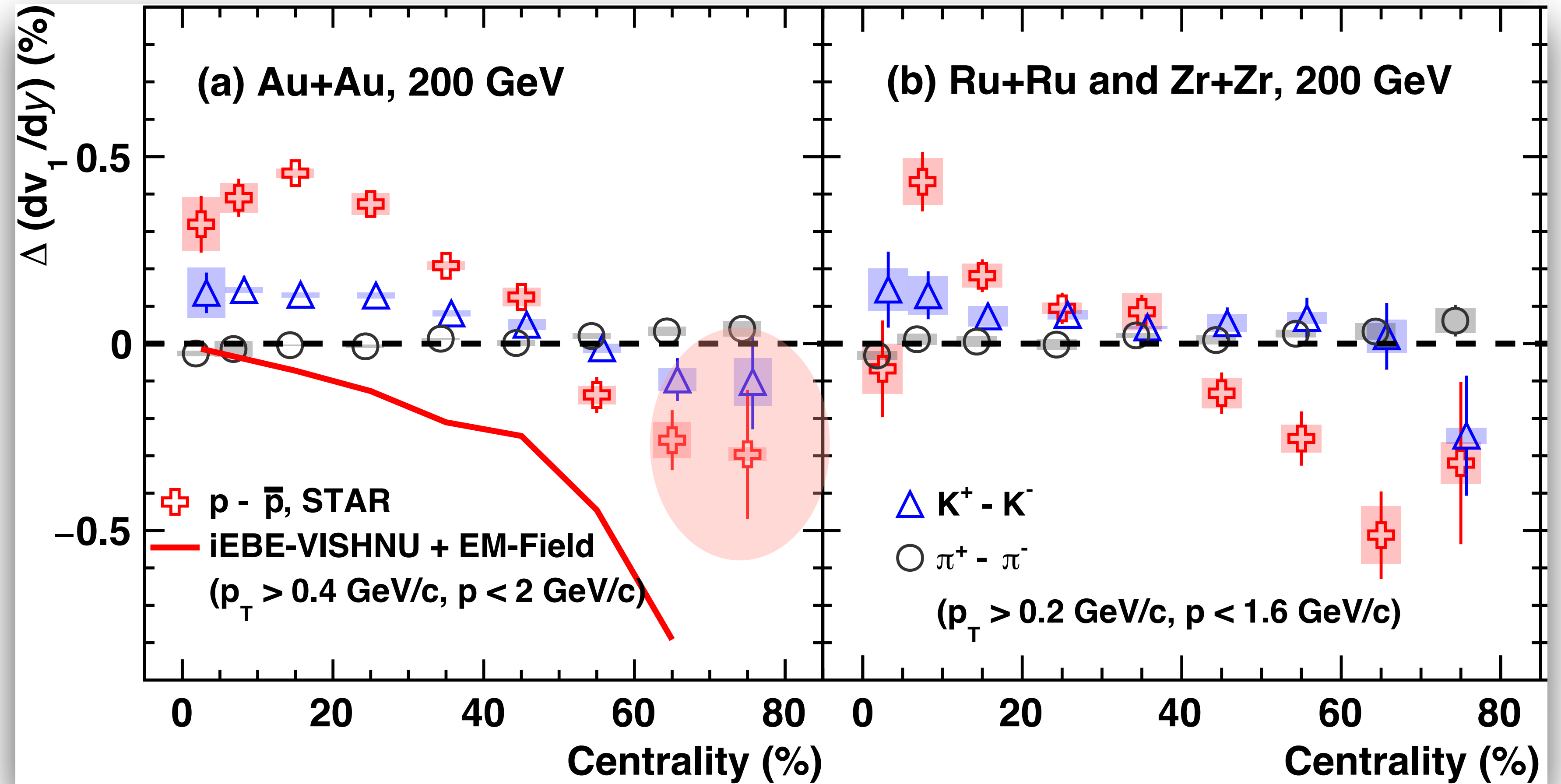


STAR, PRX 14, 011028 (2024)

- Significant splitting for proton's Δv_1 (> 5σ significance)

  (Negative Δv_1 consistent with Faraday+Coulomb dominates over Hall effect)

Charge dependent light quark directed flow



STAR, PRX 14, 011028 (2024)

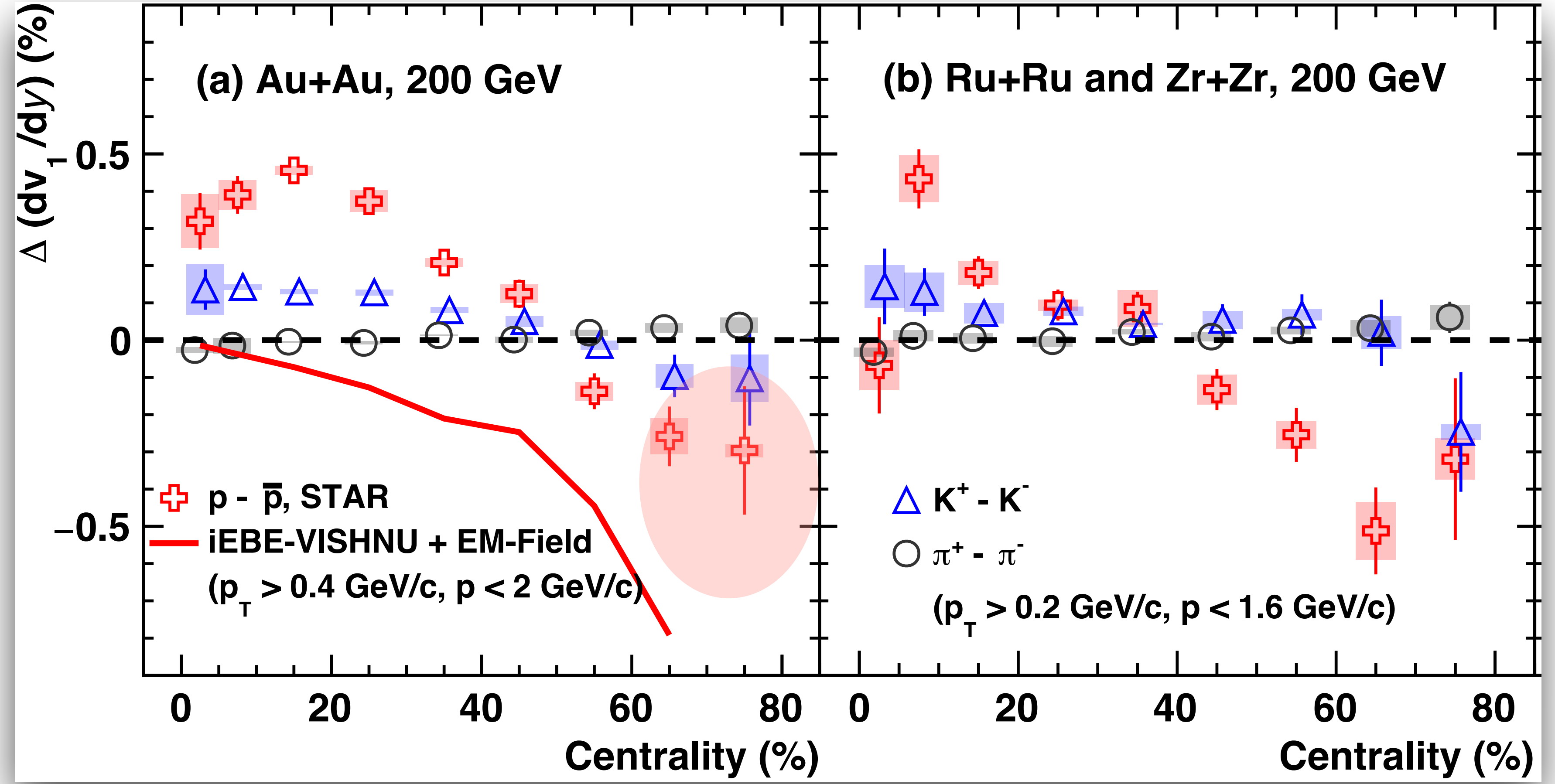
- For protons and kaons: sign change in Δv_1 in peripheral collisions

  (Negative Δv_1 consistent with Faraday+Coulomb dominates over Hall effect)

- Model iEBE-VISHNU + EM: $\sigma \sim 0.023\ \mathrm{fm}^{-1}$ (falls within a reasonable range)

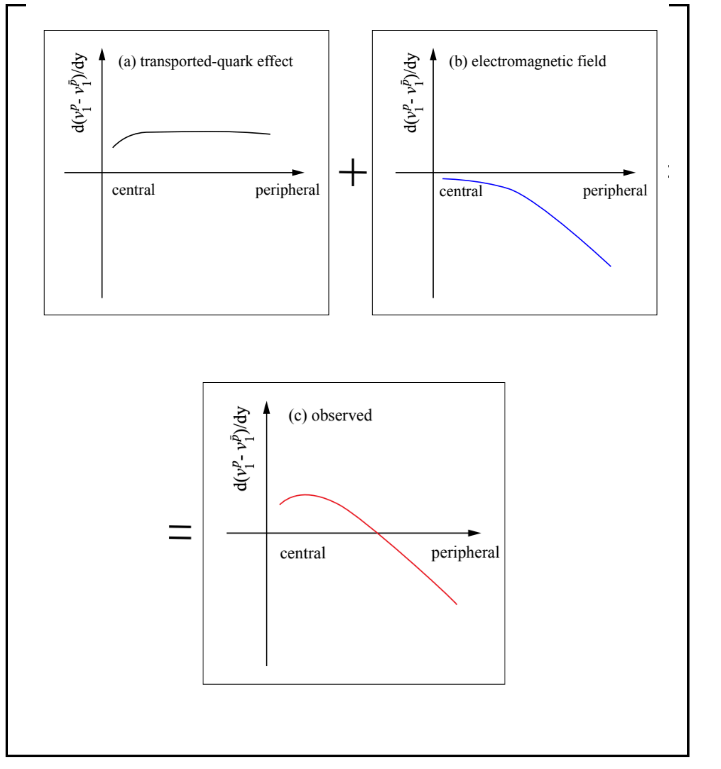
Charge dependent light quark directed flow

Observation



STAR, PRX 14, 011028 (2024)

Expectation

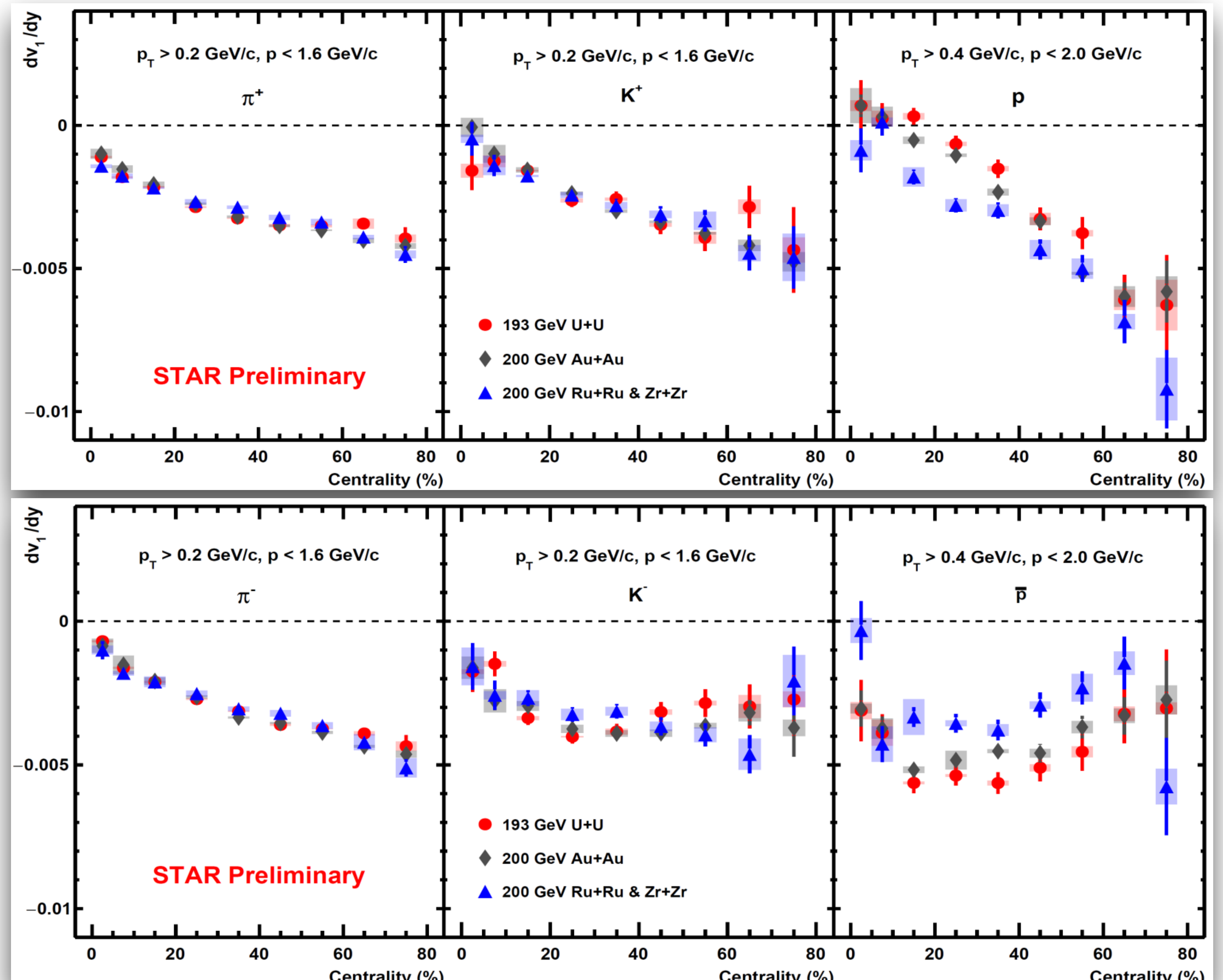


- For protons and kaons: sign change in Δv_1 in peripheral collisions

  (Negative Δv_1 consistent with Faraday+Coulomb dominates over Hall effect)

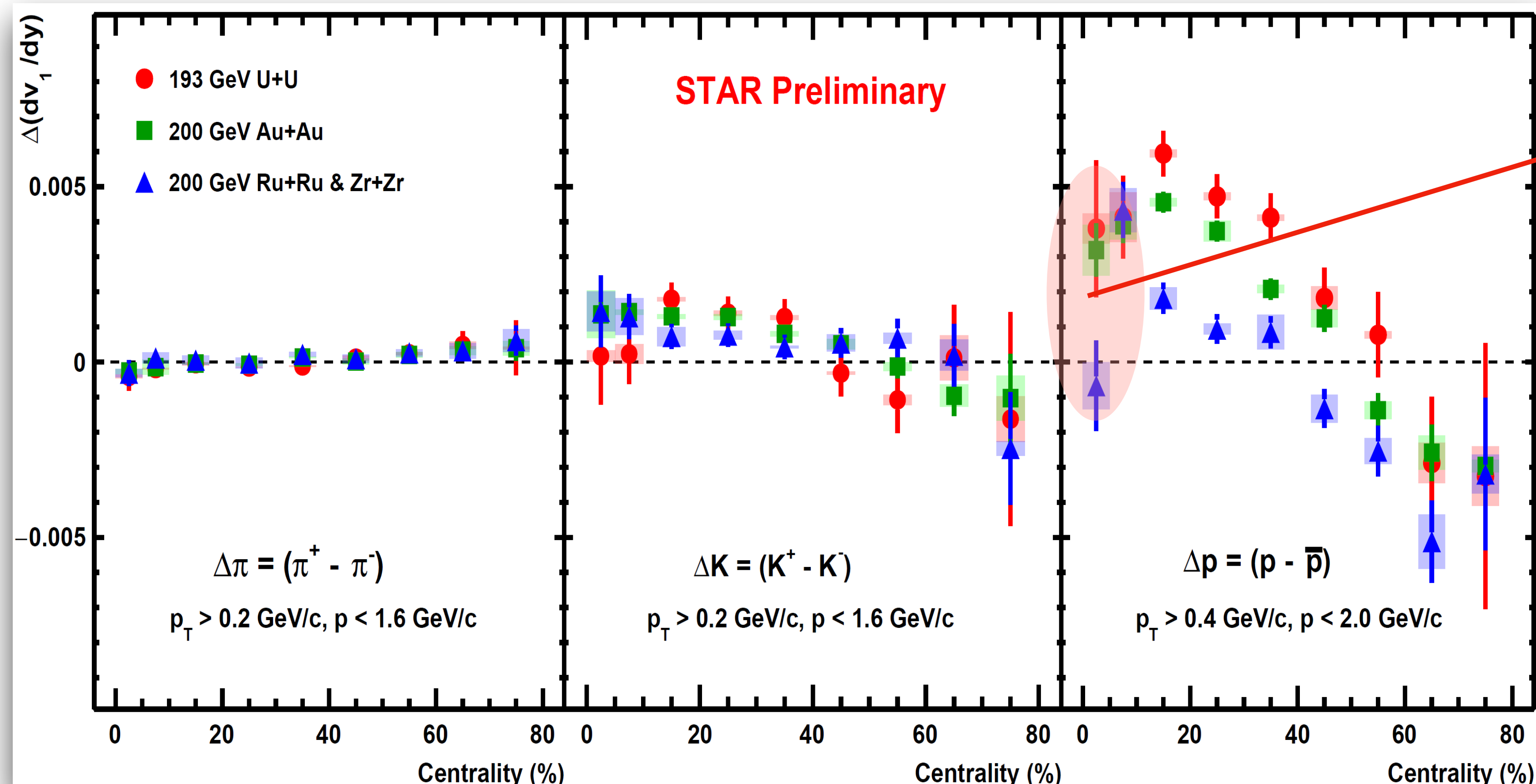
- For pions: Δv_1 ~ 0 (large uncertainty)

Light hadron dv_1/dy: system size dependence



- pions & kaons: U+U ~ Au+Au ~ Isobar
- protons: U+U < Au+Au < Isobar
- anti-protons: U+U > Au+Au > Isobar

Light hadron $\Delta dv_1/dy$: system size dependence



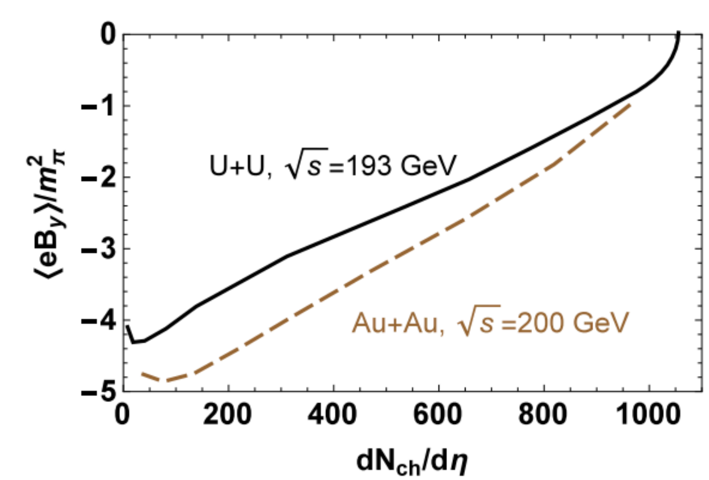
Splitting in most-central collisions
Can be related to baryon transport

Parida et al, 2305.08806

- Interplay of baryon transport and electromagnetic field effects across centralities
- Require proper modeling to understand the data

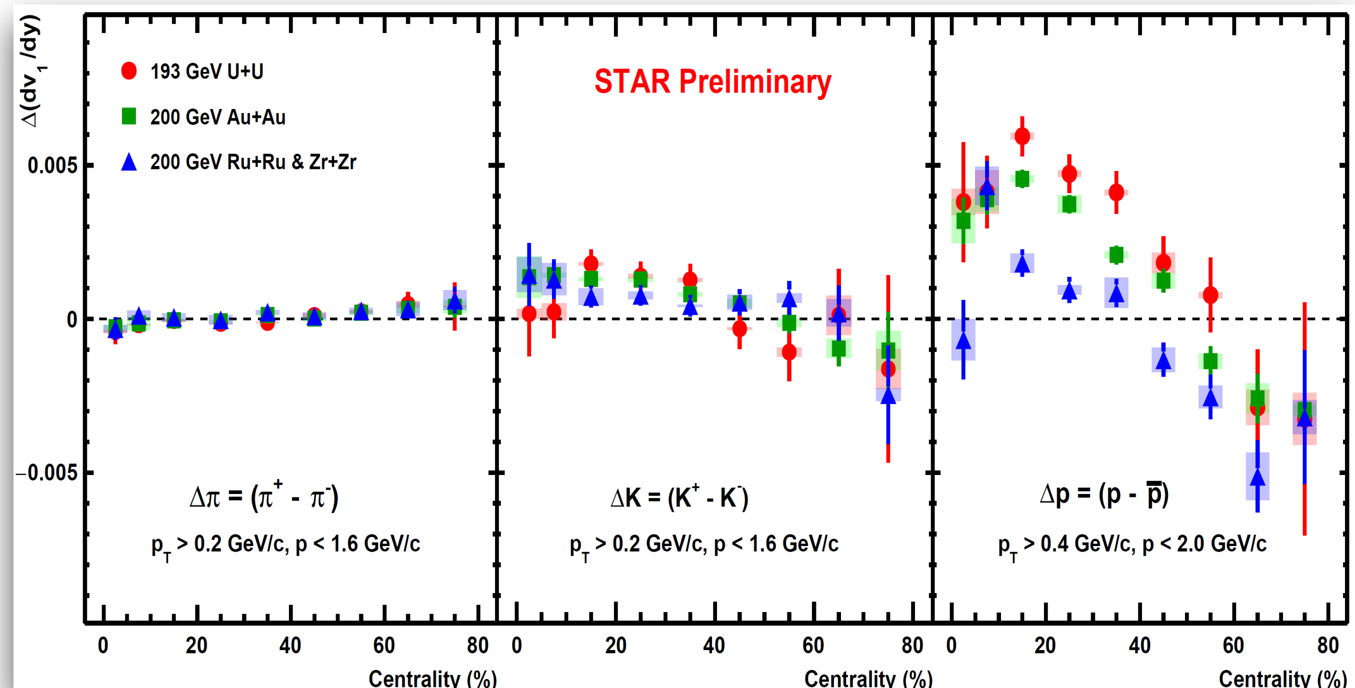
in different systems several factors to be considered:
- strength and lifetime of EM-field
- QGP lifetime and conductivity
- transport
- …

event-averaged eB_y at t=0

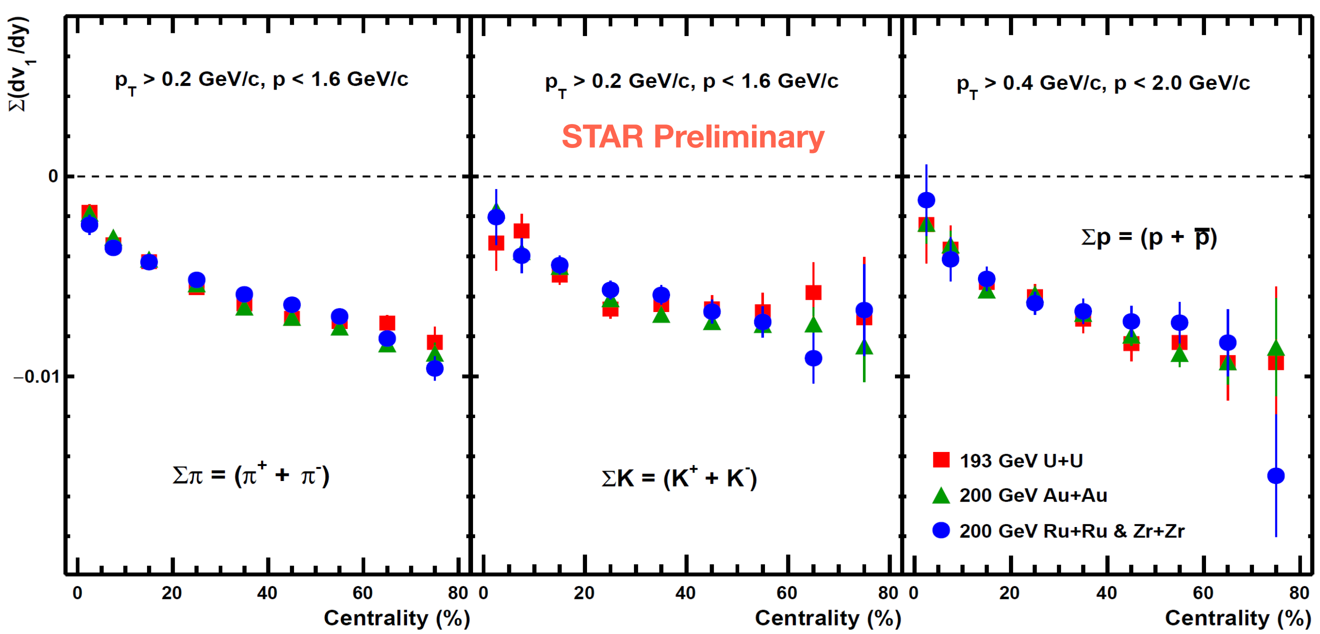


Bloczynski et al, NPA 939, 85 (2015)

Light hadron $\Delta dv_1/dy$: system size dependence

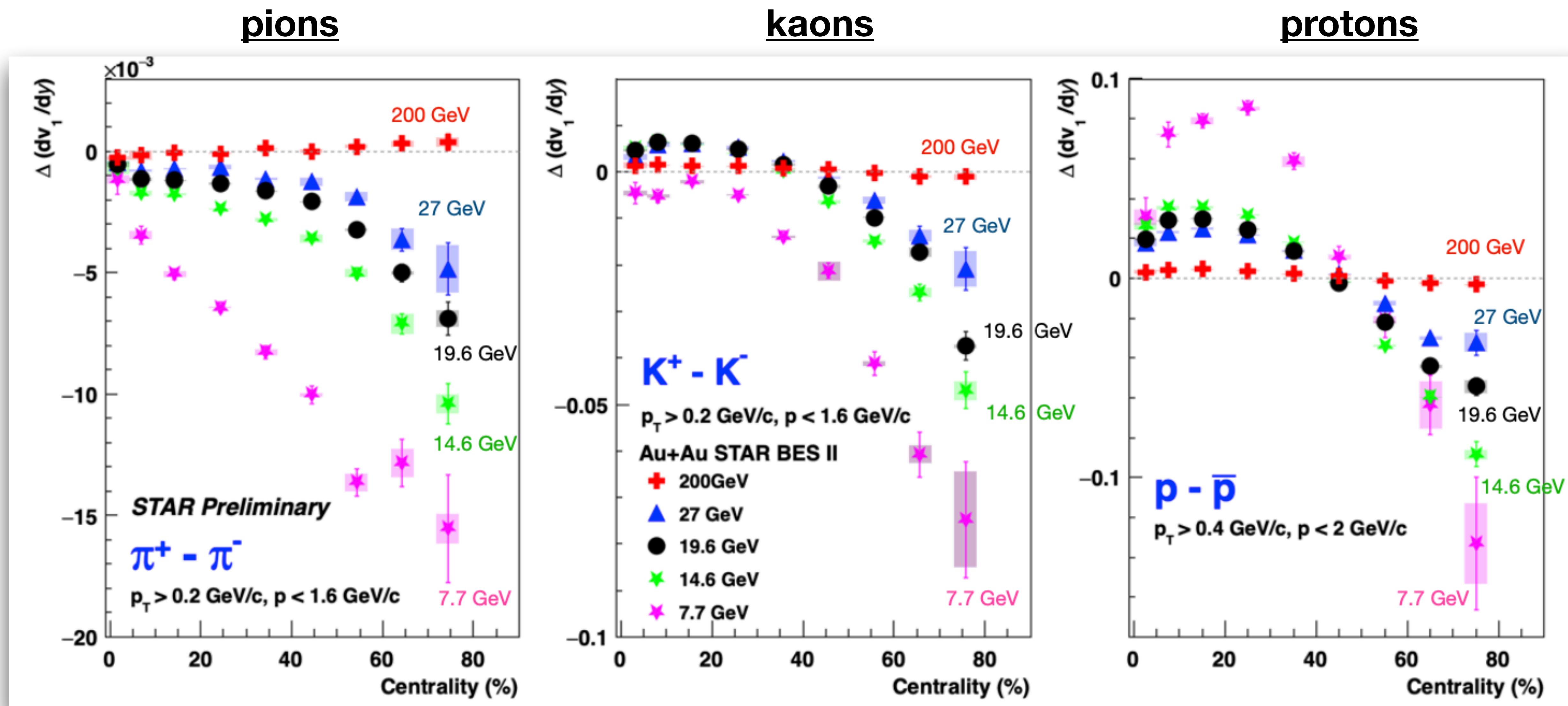


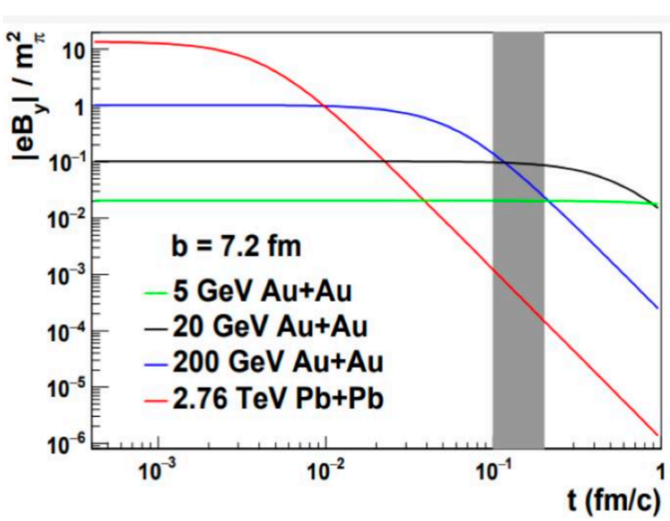
- Difference Δv_1: $h^+ - h^-$
- pions & kaons: U+U ~ Au+Au ~ Isobar
- protons: U+U < Au+Au < Isobar



- Sum Σv_1 : $h^+ + h^-$
- pions & kaons: U+U ~ Au+Au ~ Isobar
- protons: U+U ~ Au+Au ~ Isobar

Light hadron $\Delta dv_1/dy$: beam energy dependence





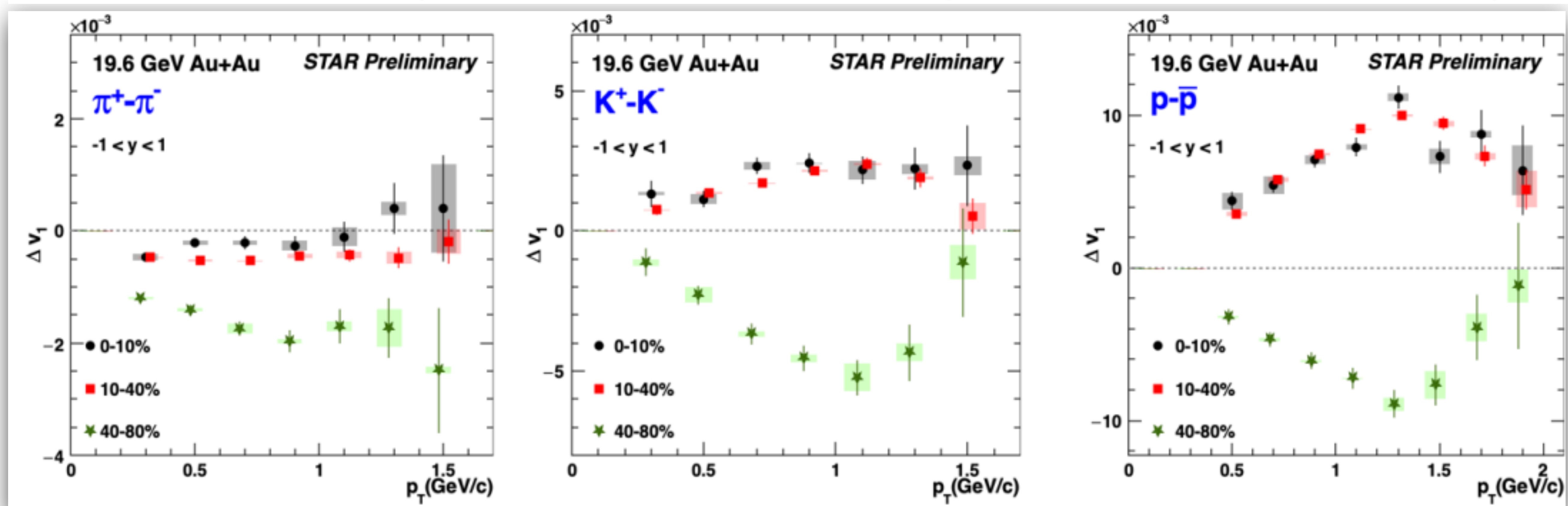
- In peripheral, negative Δv_1 increases with decreasing beam energy
- consistent with dominance of Faraday and coulomb effect

With decreasing energy:

- Nuclear passage time is large and B-field lifetime could be longer
- Lifetime of fireball could be shorter

Light hadron $v_1(p_T)$: beam energy dependence

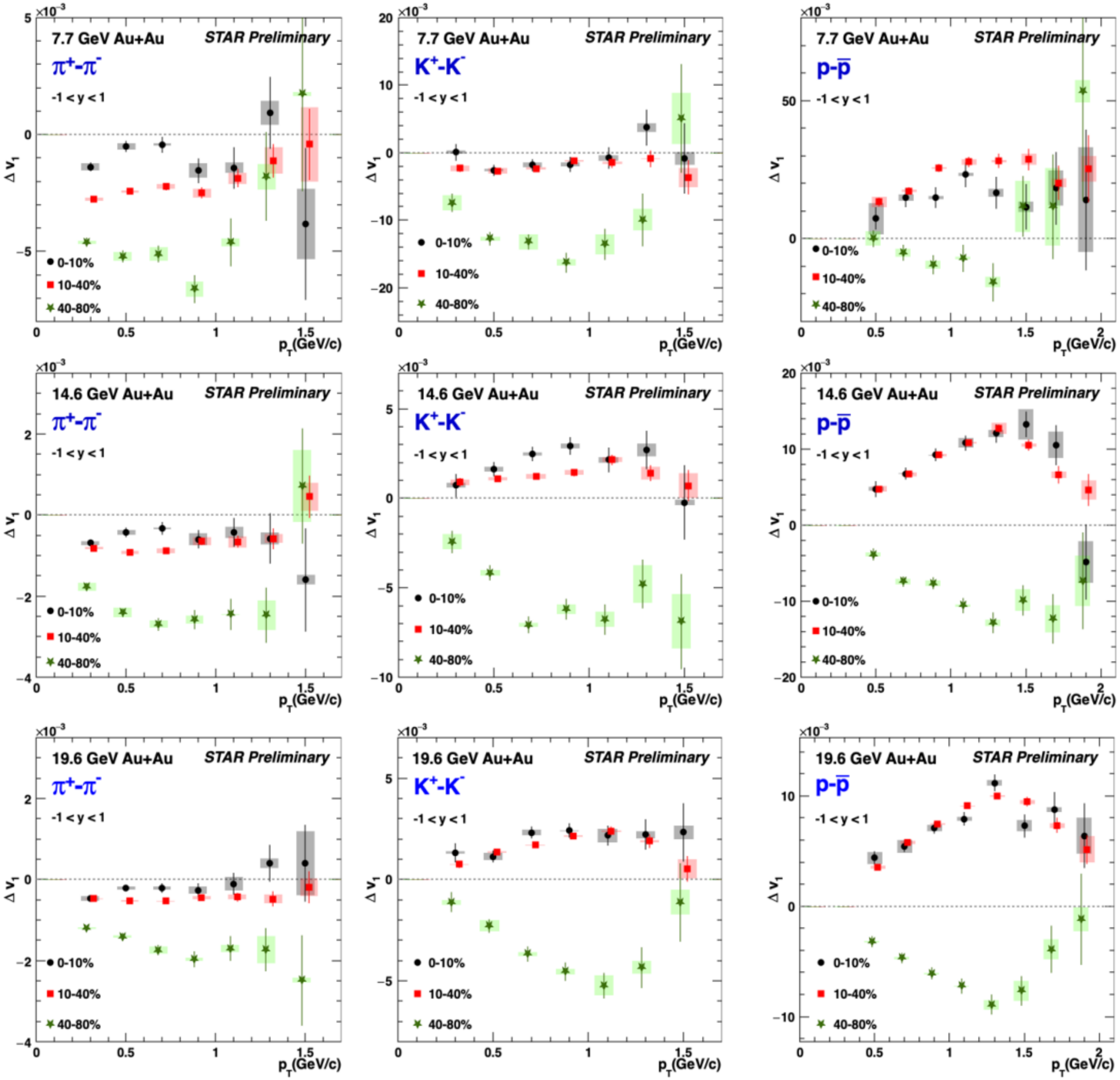
pions **kaons** **protons**



- Peripheral collisions (40-80%):
- Negative Δv_1 increases linearly with p_T
- Qualitatively Consistent with EM prediction

Light hadron $v_1(p_T)$: beam energy dependence

pions **kaons** **protons**



7.7 GeV

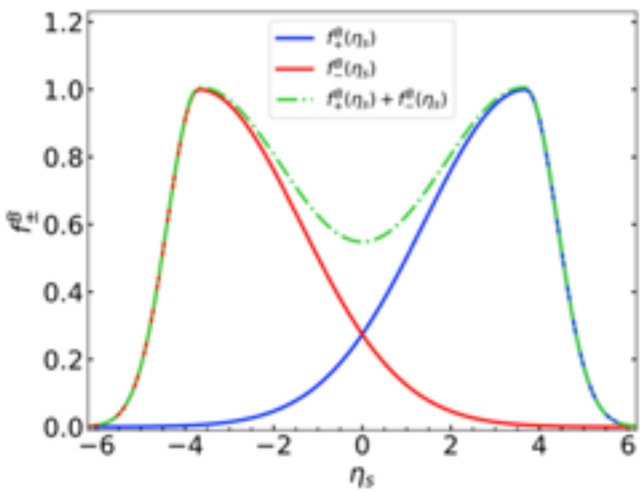
14.6 GeV

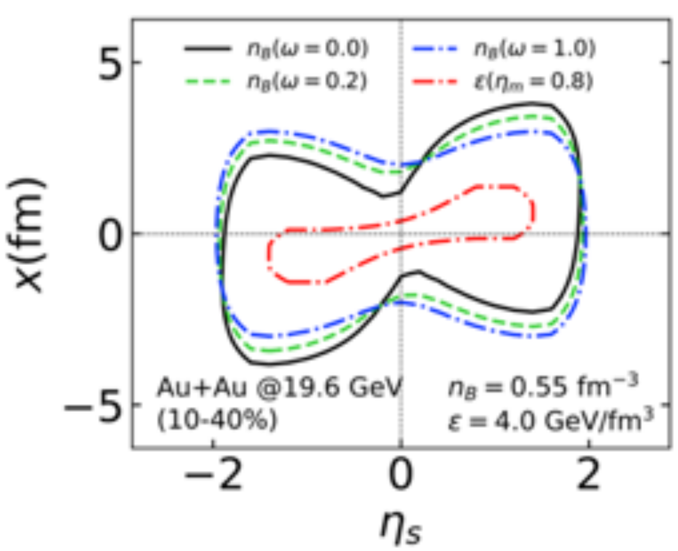
19.6 GeV

- Negative Δv_1 pattern consistent across BES energies

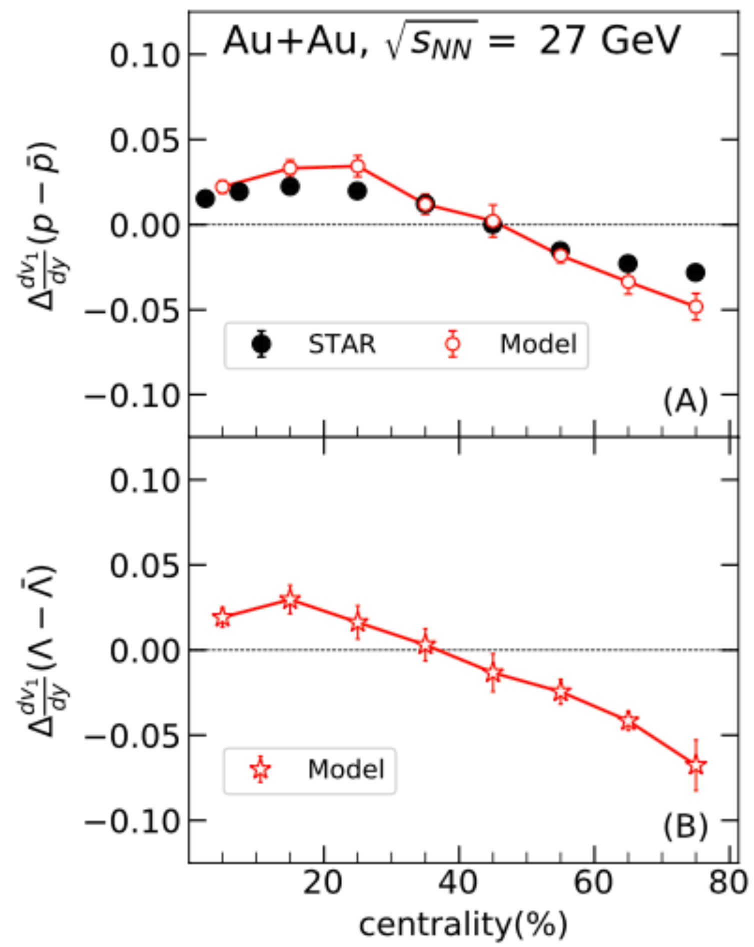
Hydro with baryonic profile

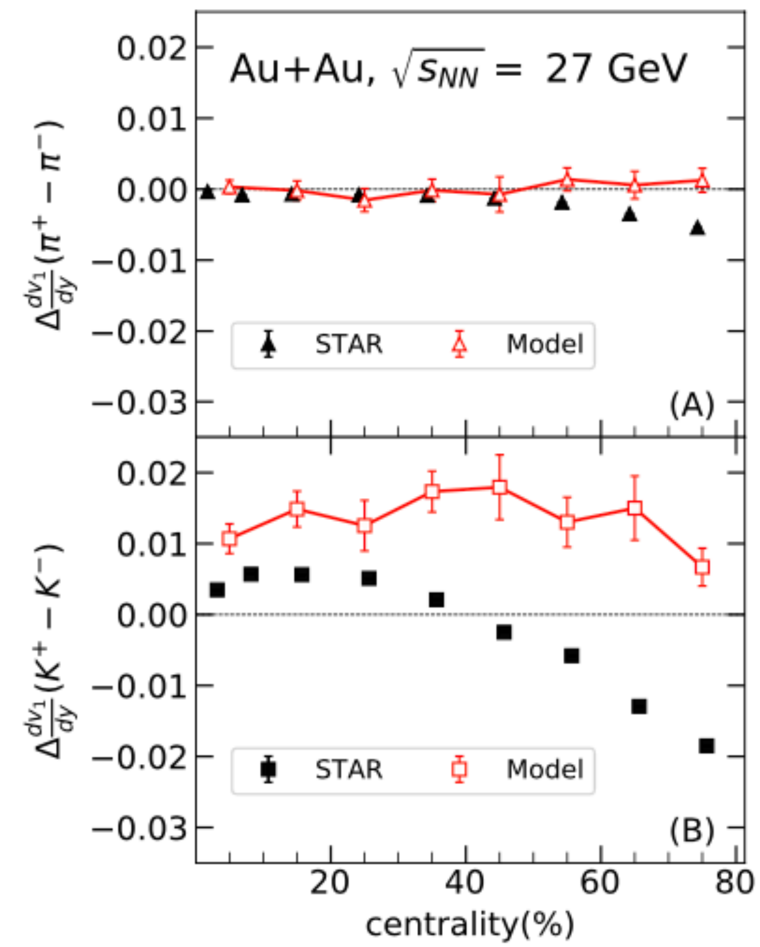
<u>Initial baryon profile</u>





<u>Δv₁ from Hydro without EM field</u>





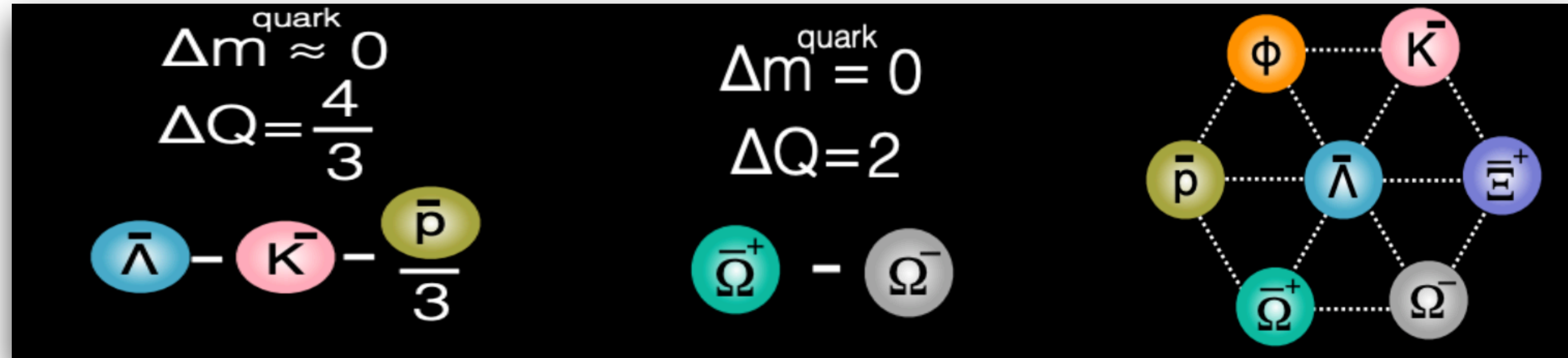
Parida et al, 2305.08806

- Hydrodynamic model with a baryonic profile (without EM) can qualitatively capture proton Δv_1
- However, it can not explain negative Δv_1 for pions and kaons

- Require modeling transport+EM to better understand Δv_1

Light hadron $\Delta dv_1/dy$: using only produced quarks

Δv_1 measured using combination of *transported-quark-free* hadrons



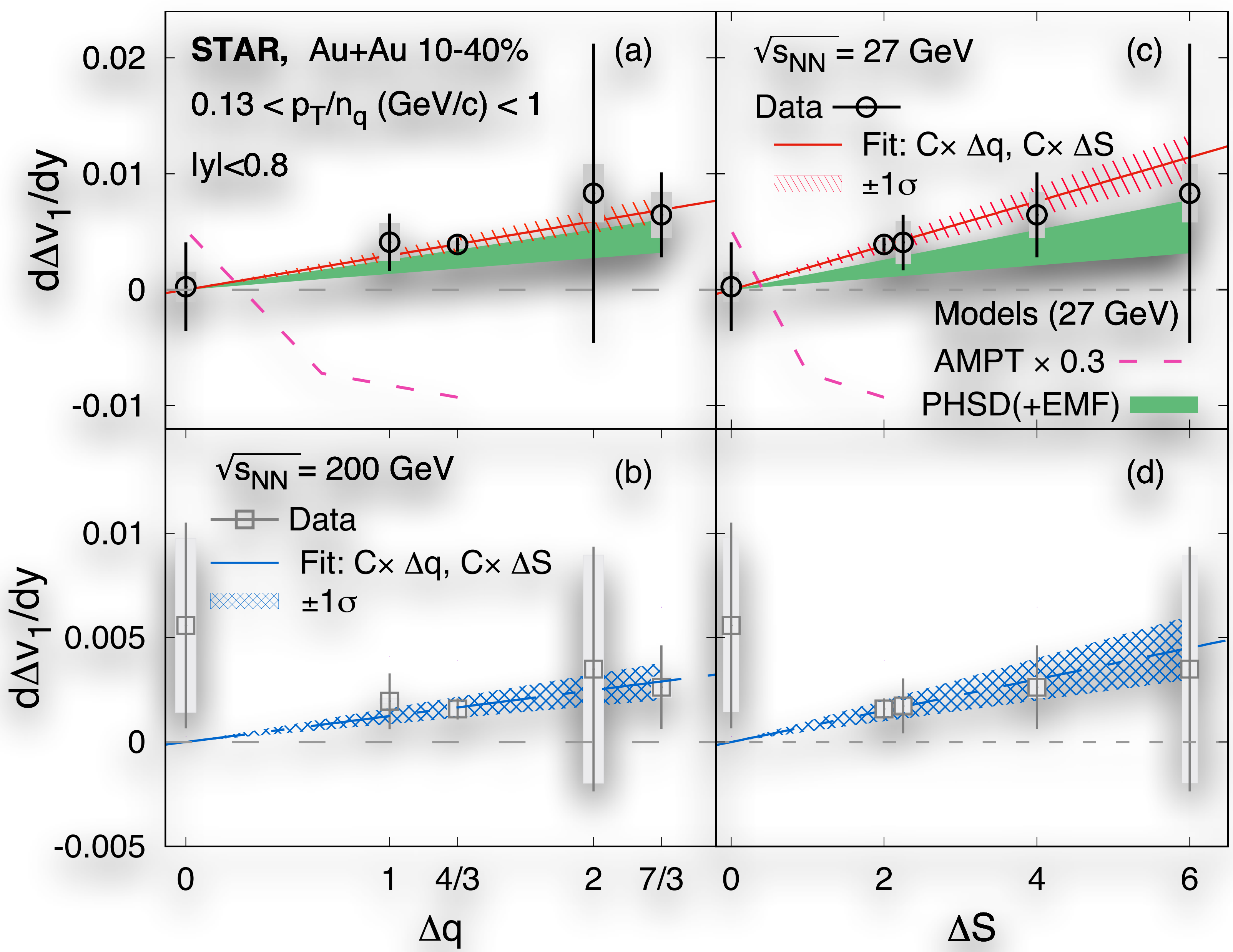
Combination of particle with similar mass but different Δq and ΔS

Index	Quark mass	Δq	ΔS	Δv_1 combination
1	$\Delta m = 0$	0	0	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^{-}(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	1	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^{-}(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
3	$\Delta m \approx 0$	$\frac{4}{3}$	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^{-}(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
4	$\Delta m = 0$	2	6	$[\bar{\Omega}^{+}(\bar{s}\bar{s}\bar{s})] - [\Omega^{-}(sss)]$
5	$\Delta m \approx 0$	$\frac{7}{3}$	4	$[\bar{\Xi}^{+}(\bar{d}\bar{s}\bar{s})] - [K^{-}(\bar{u}s) + \frac{1}{3}\Omega^{-}(sss)]$

Sheikh et al, PRC 105, 014912, (2022)

- Study Δv_1 as function of charge difference (Δq) and strangeness difference (ΔS)

Light hadron $\Delta v_1/dy$: using only produced quarks



STAR, 2304.02831

- Δv_1 is positive
- Δv_1 increases with Δq and ΔS
- Δv_1 increases with decrease in beam energy

Δv_1 consistent with dominance of Hall effect over Faraday+coulomb in mid-central collisions

New Proposals:

2D fit to decompose the correlation between Δq and ΔS — *Nayak et al PLB 849, 138479 (2024)*

Role of baryon transport, some cases with $\Delta q, \Delta S \neq 0$ also have $\Delta B \neq 0$ — *Parida et al, 2305.08806*

Summary

- Background strong EM field rich in physics and interdisciplinary
  (pre-condition for CME, QCD phase transition, chiral symmetry and many more)

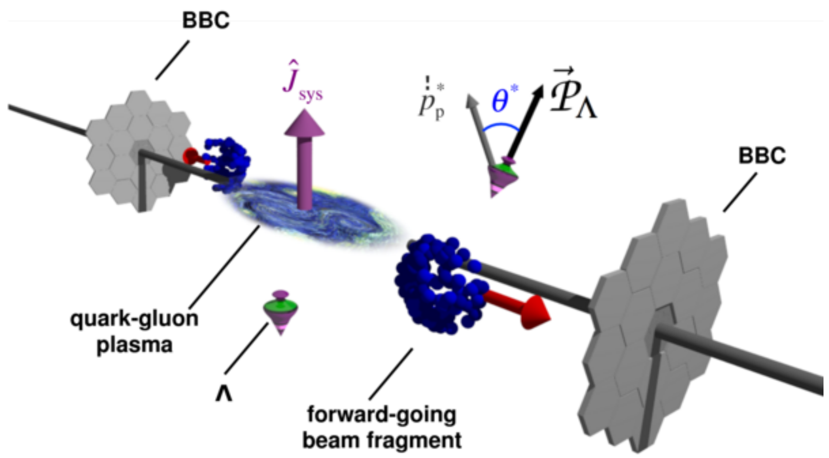
- Measurement of charge dependent directed flow (Δv_1)
  - Coulomb effect in asymmetric collisions (Cu+Au)
  - For charm hadrons (early production) Hall effect is relevant
  - For light hadrons: dominance of Faraday and coulomb in peripheral collisions

    Imprints of electromagnetic field effects observed in HIC

  - Constrain strength and lifetime of EM-field
  - Provide knowledge of electrical conductivity of the QGP medium
  - Provide information on transport mechanism

- More theory input is needed to understand system-size and energy dependence of Δv_1

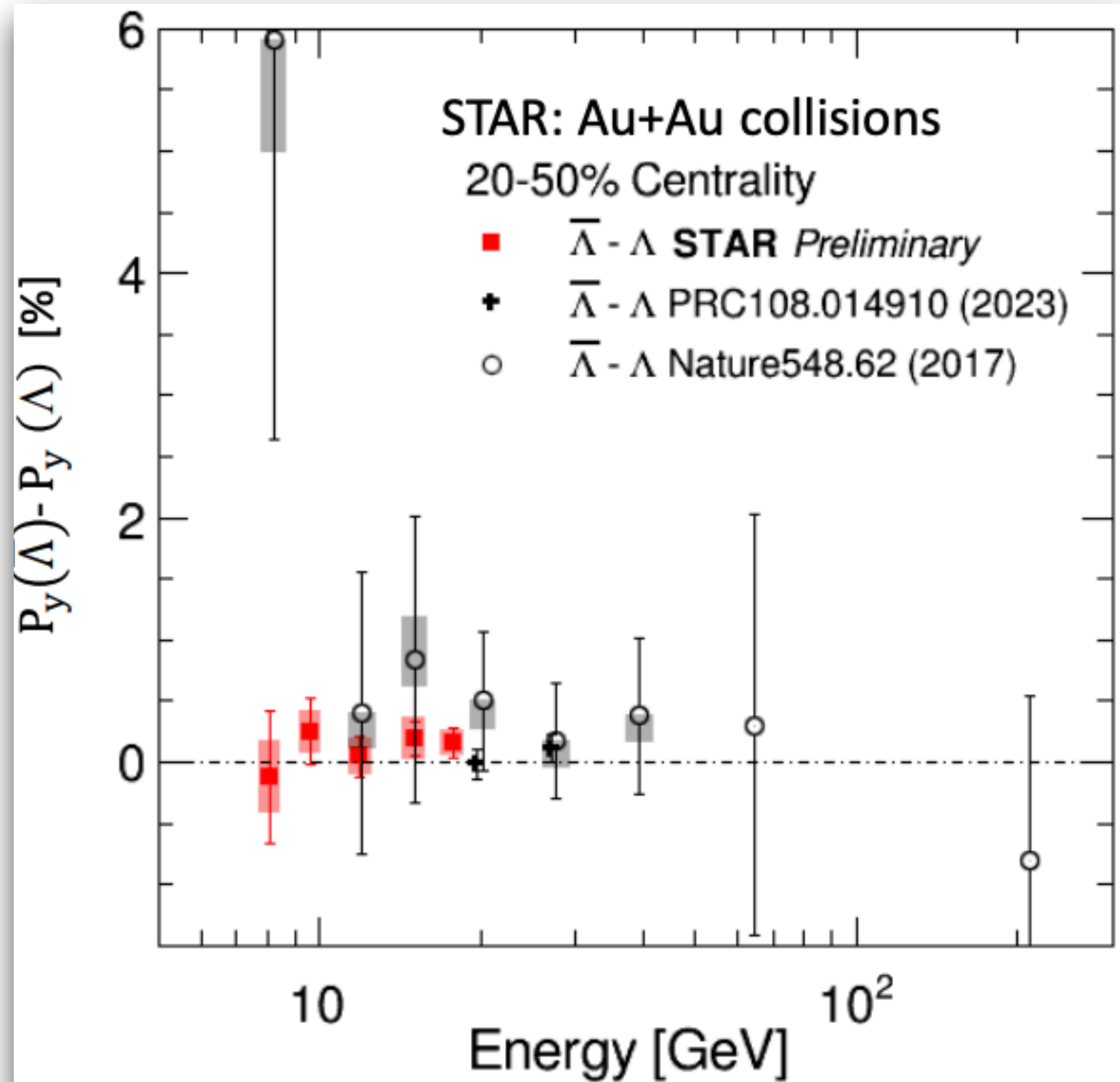
Outlook-I: Polarization difference $P_\Lambda - P_{\bar{\Lambda}}$



Global spin polarization:

- $$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\text{Res}(\Psi_1)}$$

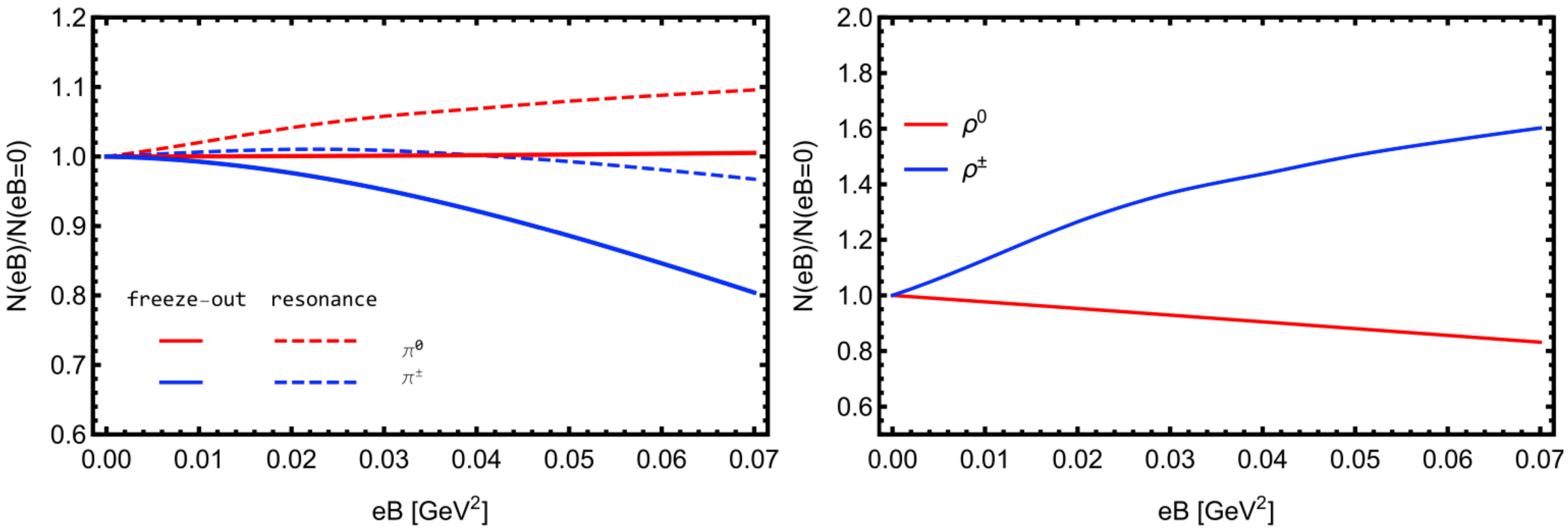
$$P_\Lambda - P_{\bar{\Lambda}} = 2\frac{\mu_\Lambda B}{T}$$



From precise BES-II data:

- Upper limit on late-stage B-field:
- B < 9.4×10^{12} T at 19.6 GeV and B < 1.4×10^{13} T at 19.6 GeV
- Polarization of hyperons with different magnetic moments (Λ, Ξ, Ω)

Outlook-II: Neutral and charged vector mesons



Kun et al, PLB 809, 135706 (2020)

$\rho^0 \to \pi^+\pi^-, \rho^\pm \to \pi^0\pi^\pm$

- Under B-field, one expect $N_{\rho^\pm} > N_{\rho^0}$ from **Landau level splitting** (isospin violation)
  $\epsilon^2_{n,s_z}(p_z) = p_z^2 + (2n - 2\ \mathrm{sign}(q)s_z + 1)\,|\,qB\,| + m^2$
- $K^{*\pm}, K^{*0} \to$ easier reconstruction, negligible feed down effect
- Yield and ratios ($K^{*\pm}/K^{*0}$) can be useful in late-stage B-field and possibility of many associated phenomenon (landau splitting, vector meson condensation ….)
  $K^{*0} \to K^\pm\pi^\mp,\ K^{*\pm} \to K^0_S\pi^\pm$

$K^{*0}(d\bar{s}):\ \mu_d \approx -0.97,\ \mu_{\bar{s}} \approx 0.61\mu_N$
$K^{*+}(u\bar{s}):\ \mu_d \approx 1.85,\ \mu_{\bar{s}} \approx 0.61\mu_N$

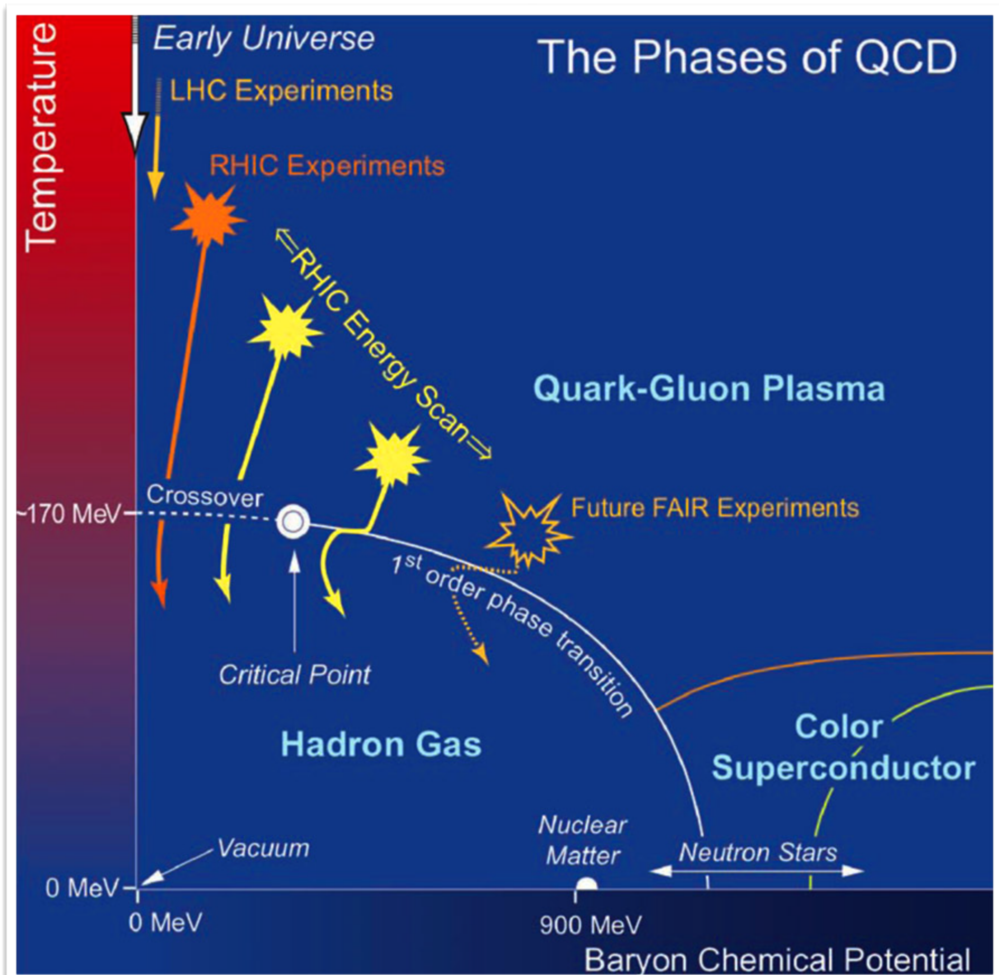
Stay tuned till upcoming Quark Matter

Thank you for your attention

Many thanks to STAR colleagues for discussion

QCD phase diagram and RHIC Beam Energy Scan

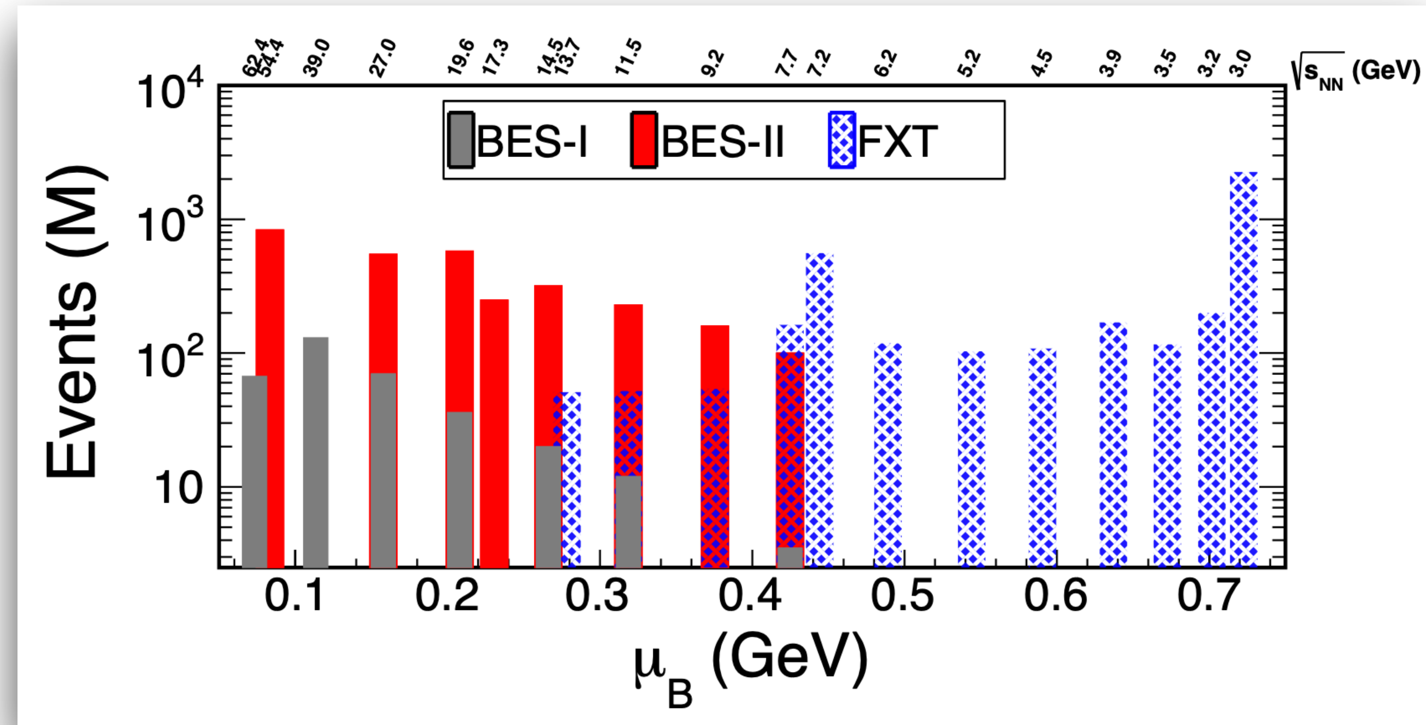
Conjectured QCD Phase diagram



Partonic dominant → Hadronic dominant

Meson dominant → Baryon dominant

BES Program:



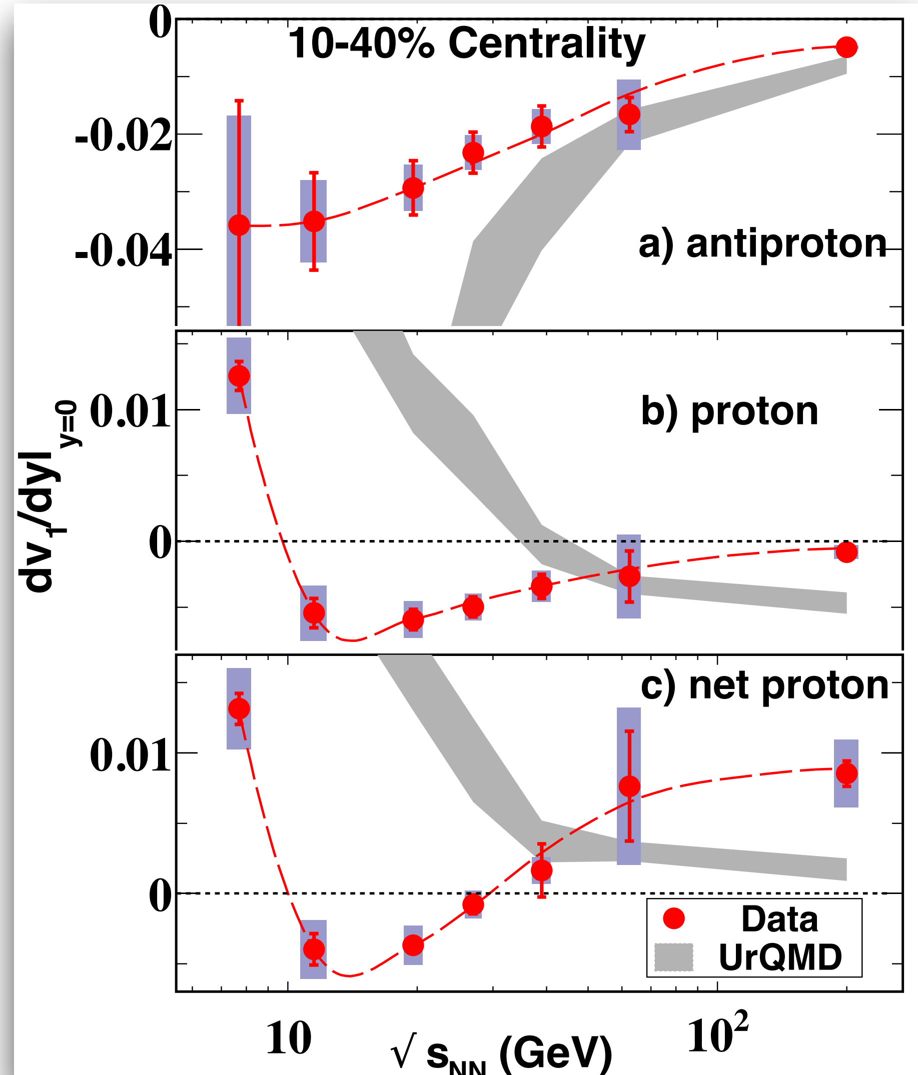
Collider: 7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27, 39, 54.4, 62.4, 200 (GeV)
Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7, 9.2, 11.5, 13.7 (GeV)

most precise data to map the QCD phase diagram

- Find signatures of Phase Transition
- QCD Critical point
- Turn-off of QGP signatures

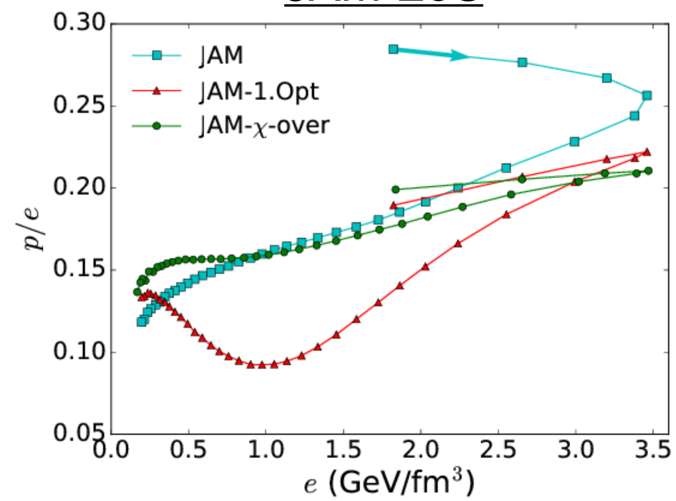
Directed flow from BES-I

BES-I STAR: PRL 112, 162301 (2014)

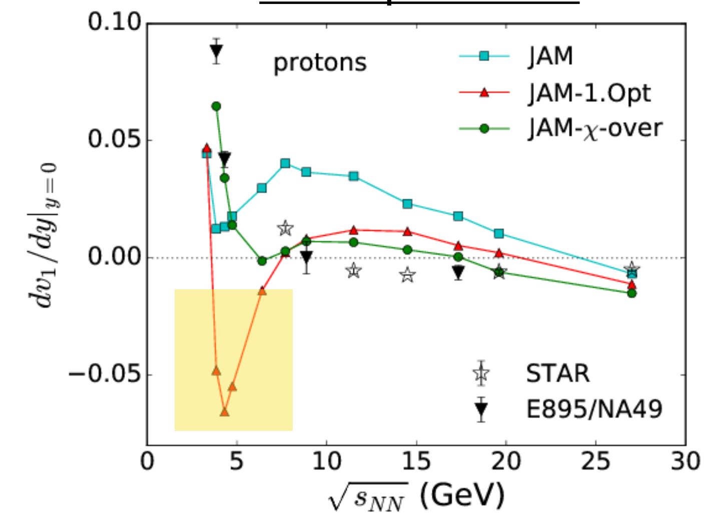


Model

JAM EoS



JAM: proton v_1



At 1st order phase transition, pressure drops as speed of sound goes to zero

Y. Nara et al, PLB 769, 543-548 (2017)

Primary observations

Around 10-20 GeV:

- proton v_1 changes sign
- net-proton v_1 change sign twice with a minima

Features qualitatively resemble the model prediction with 1st order phase transition